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COLUMBIA RIVER THERMAL EFFECTS STUDY. VOLUME I. BIOLOGICAL EFFECTS STUDIES

Environmental Protection Agency

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Atomic Energy Commission
National Marine Fisheries

January 1971

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COLUMBIA RIVER THERMAL EFFECTS STUDY

VOLUME I: BIOLOGICAL EFFECTS STUDIES

Environmental Protection Agency
in cooperation with
Atomic Energy Commission
and the
National Marine Fisheries Service,
U.S. Department of Commerce

January 1971

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FOREWORD

The Columbia River Thermal Effects Study was undertaken in pursuit of the policies and objectives of the Federal Water Pollution Control Act, particularly as amended by the Federal Water Quality Act of 1965, which required the establishment of water quality standards for the protection and enhancement of water quality throughout the United States. In the process of establishing standards during the period 1965-1968, the State and Federal water pollution control agencies recognized water temperatures as an important factor affecting water uses, both directly, as in the case of aquatic life, and indirectly, as in the synergistic effects of temperature with other parameters such as dissolved oxygen. In attempting to define temperature requirements in the standards, however, pollution control authorities encountered insufficient scientific knowledge and agreement on the precise limits needed to protect water uses.

The Columbia River Thermal Effects Study was initiated in July, 1968, in response to the specific problem of two inconsistent temperature standards adopted for the Columbia River by the States of Oregon and Washington, which share it as a border. Before attempting to resolve these inconsistencies, the State and Federal pollution control agencies could benefit from improved knowledge on the temperature requirements and tolerances of the Columbia's Pacific salmon and improved techniques for evaluation and prediction of the temperature in the Columbia system. The report of the study consists of two volumes. The first concerns the biological effects of water temperature on Pacific anadromous fish in the Columbia River

system. The second describes the application of mathematical models to the Columbia River for prediction of water temperatures.

In the Pacific Northwest, standards were generally required to protect the economically important Pacific salmon, a cold-water anadromous species. The upriver runs of Columbia River fish resources have been reduced and endangered by the physical alteration and blockage of migration routes by the Nation's largest system of dams and reservoirs. The quality of the aquatic environment has also been modified by the discharge of pollutants and impoundment of the river's flow in a series of reservoir lakes reaching into Canada. Particularly regarding temperature quality, the Columbia River temperatures have been both spatially and temporally altered by man's activities and use of the water resources of the Region.

At about the time standards were established, public and private electric power interests in the Northwest announced forecasts of vastly increased power demands. The hydroelectric power potential of the Northwest is nearly exhausted, and thermal power sources are planned to meet future needs. This presented further potential for modification of the thermal regime of the Columbia River system. Initially, power producers assumed the possibility of using Columbia River system waters for once-through cooling at thermal power plants. The prospect, however, of numerous discharges of large quantities of heated effluents to inland waters has since prompted the Region's water pollution control agencies to issue policy statements which require complete offstream cooling for thermal power plants located

on inland waterways in the Basin. Power planners have accepted this policy of offstream heat controls throughout the Basin.

Among the remaining environmental problems associated with increased thermal power production is the projected use of the existing hydroelectric system for power-peaking, with thermal units providing the baseload, or firm power. The potential water quality effects of exaggerated flow modification caused by these peaking operations emphasizes the need to understand the existing thermal regime of the Columbia River system. The prospects of industrialization, upon which the power demands are based, hold further potential for environmental impacts which would require sound standards and controls.

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I - INTRODUCTION

Purpose

The purpose of this report is to present the available knowledge on temperature requirements and tolerances of anadromous fish in the Columbia River. The material is intended for use by State and Federal water quality agencies in their ongoing programs for prevention, control and abatement of pollution, particularly in connection with water quality standards.

Scope

The information and data presented in this report are limited to conditions and species found in the main stem Columbia River in those areas remaining accessible to anadromous fish. Figure 1 presents a map of the area. The material includes information from the literature and from the files of Northwest fisheries agencies, with particular emphasis on new knowledge developed by the research studies conducted as part of the Columbia River Thermal Effects Study (CRTES). Although related scientific work is reported in the literature on thermal effects on salmonids and other fish, much of it is not directly applicable to Columbia River conditions or fish. Therefore, references shown in the bibliography are limited to studies having direct application to the Columbia River species and habitat.

The research studies conducted as a part of the CRTES, and listed in Appendix A, were designed to develop immediate answers to the needs of water quality agencies of the Northwest in considering the adequacy of

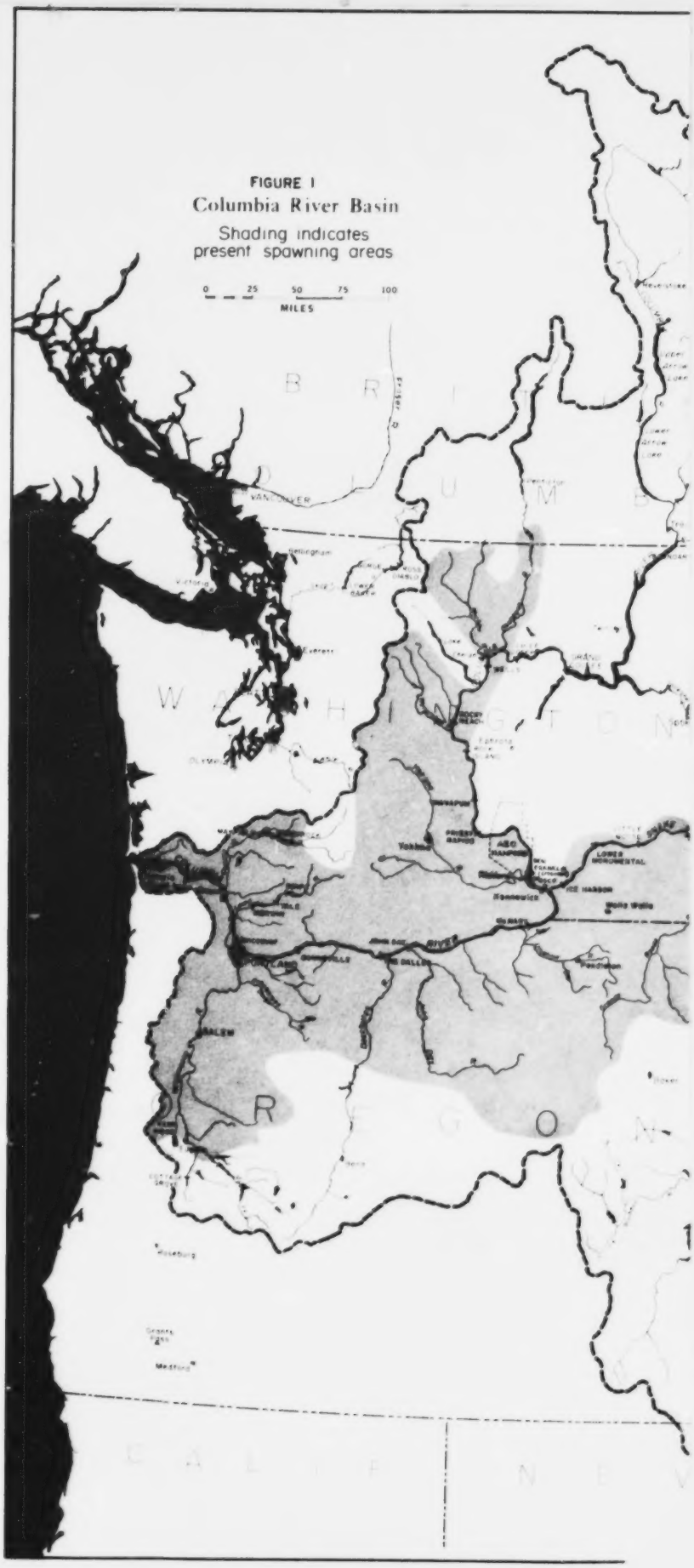
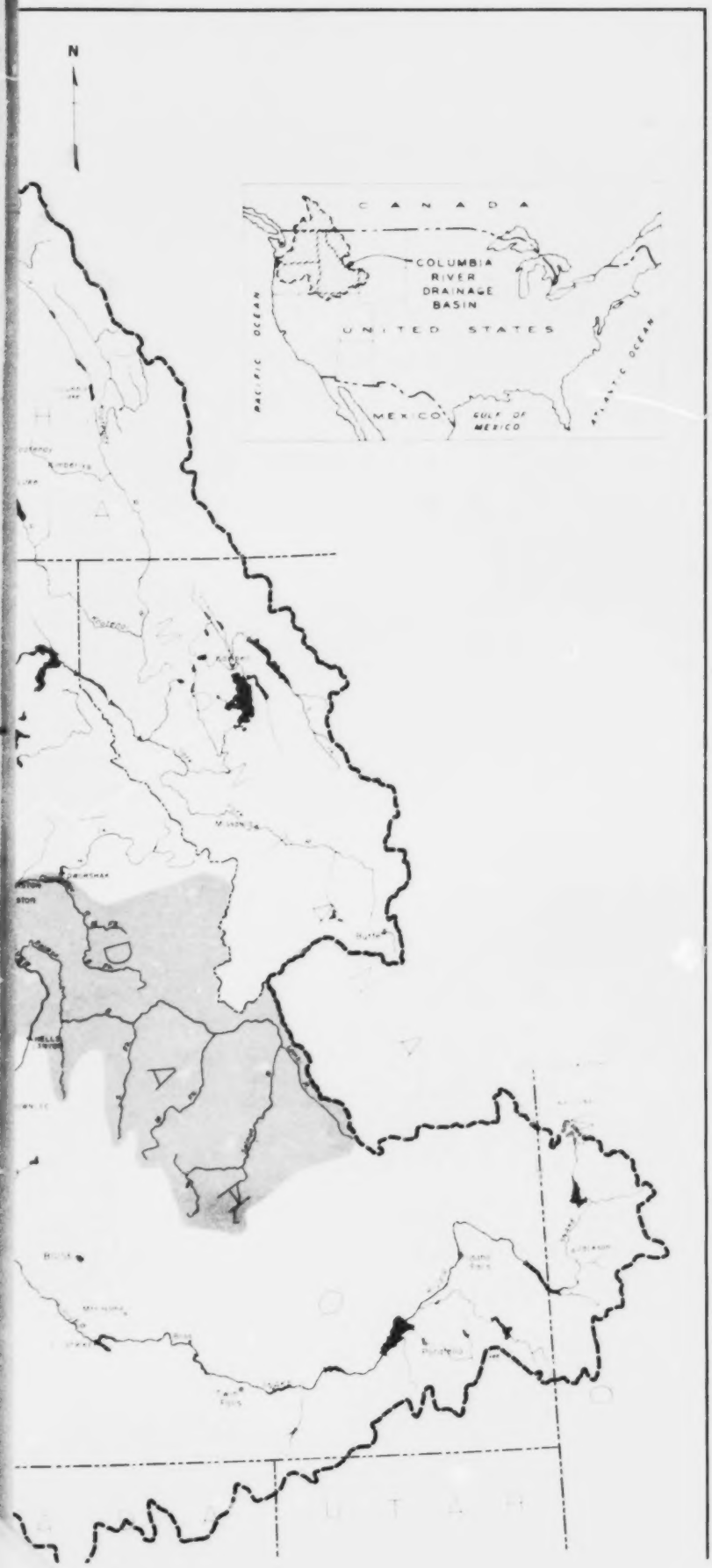


FIGURE 1
Columbia River Basin
Shading indicates
present spawning areas
0 25 50 75 100
MILES
BRITISH COLUMBIA
VANCOUVER
WASHINGTON
OREGON
CALIFORNIA
IDAHO
Fraser R.
Yakima
Snake R.
Grande Ronde
John Day River
Deschutes
Umatilla
Walla Walla
Klamath
Salem
Medford
Ice Harbor
Lower Granite
Dworshak
Hells Canyon
Pahsimeroi


N
CANADA
COLUMBIA
RIVER
DRAINAGE
BASIN
UNITED STATES
PACIFIC OCEAN
ATLANTIC OCEAN
MEXICO
GULF OF
MEXICO
UTAH

water quality criteria limits and goals for water temperatures in the Columbia River. In all the temperature criteria adopted in the Northwest, two conditions were set: maximum upper limits for protection of aquatic life, and incremental increases within those upper limits. Therefore, the studies were oriented to more specifically define both the maximal temperatures for salmonids and the tolerances of those fish to changes in temperatures within that range. The studies were further oriented to the particular temperature-modifying influences found or anticipated in the Columbia Basin: impact of impoundment and reservoir releases and discharges from thermal power plants. Although the latter thermal source has since been obviated by water quality agency preventive policies, much of the study emphasis related to questions of large thermal discharges, and this material is included for academic value.

The field studies were limited to the most critical aspects of the lethal and sublethal thermal effects at various life stages of the anadromous fish. It was recognized that two years is not adequate time to conclude research of a subject of this complexity. However, by concentrating efforts on those areas of immediate concern, much could be learned upon which to base the needed decisions. By their nature, many of the projects conducted as a part of the study are site-specific to conditions in the lower Columbia River near Prescott, Oregon and in the Hanford reach of the Columbia River. Prescott is the proposed site of the first privately-developed nuclear power plant in the Northwest; the Hanford reach is the last

unimpounded reach of the river above the estuary and the site of the only existing nuclear plants in the Region, operated by the Atomic Energy Commission.

Authority and Participants

The CRTES was authorized by the Secretary of the Interior in February, 1968.[1/] In his approval of the water quality standards for the State of Washington, the Secretary recognized that the temperature criteria set by the State for the Columbia River were inconsistent with those set by the State of Oregon for the same waters. Rather than disapprove the temperature criteria portion of Washington's standards, or reconsider approval of Oregon's standards, the Secretary directed that the Thermal Effects Study be completed to provide further knowledge with which to reconsider the adequacy of temperature criteria on the Columbia River.

The Northwest Regional Office of the Environmental Protection Agency was directed to provide leadership in those studies. To take

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1/ Two Presidential Orders for reorganization took effect in the interim between study initiation and report publication. The first was effective October 3, 1970, and created the National Marine Fisheries Service in a new National Oceanic and Atmospheric Administration in the Department of Commerce to replace the former Bureau of Commercial Fisheries in the Department of the Interior. The second was effective December 3, 1970, and created an independent Environmental Protection Agency to incorporate many Federal programs concerning the environment and abolishing the Federal Water Quality Administration (formerly the Federal Water Pollution Control Administration) in the Department of the Interior. The water pollution control responsibilities and authorities of the Secretary of the Interior were thus transferred to the Administrator of the Environmental Protection Agency.

full advantage of the expertise, programs, and facilities already devoted to research on the effect of heat and anadromous fish in the Columbia, the National Marine Fisheries Service (NMFS) and the Atomic Energy Commission were included as participants in the research studies. The Atomic Energy Commission's (AEC) research was conducted by Battelle Northwest (BNW) which operates the AEC's Pacific Northwest Laboratory (PNL) at Richland, Washington. The research program was developed by the three agencies, with many ongoing studies and research projects used or adapted as part of the CRTES. At the conclusion of each project, the research report was furnished to the Environmental Protection Agency (EPA) for incorporation into the biological effects report. These studies are referenced as appropriate to the subject and scope of this report and are not summarized in total. EPA has not assumed responsibility for publication of the individual research reports. The author agency should be contacted for copies or further information on any of the contributing manuscripts, listed in Appendix A.

To advise in the conduct of the research program, the ad hoc Technical Advisory Committee on Biological Effects was organized. Advisory Committee membership (Appendix B) includes State and Federal fisheries and water quality agencies, power company representatives, and Federal power and water management agencies. The Advisory Committee reviewed research study proposals, which improved the studies and avoided duplication of effort.

Report Organization

Chapter II presents a summary of the major conclusions bearing on the water quality requirements of the Columbia River fish resources. Chapter III, entitled "General Considerations," develops a framework of concepts and definitions which are applicable to the biological information presented in this report and which transcend the various life history stages which are discussed in subsequent chapters. The remainder of the report presents the compilation of available knowledge pertinent to the temperature requirements of Columbia River fish. It is organized into four chapters: adult anadromous fish, juvenile anadromous fish, non-salmonid fishes, and secondary production organisms. Discussion of thermal tolerance and temperature effects is presented in each chapter as appropriate.

The discussion in Chapters III and IV roughly corresponds with the succession of activities of an anadromous fish: e.g., juvenile migration timing, rate of movement, distribution, etc. The relevance of some of the subjects to thermal effects may not be obvious to the reader. If one were considering the effects on a migrating salmon of a single point source of heat or a general warming of a river, one would ask a variety of questions regarding the fish's activities. This report presents information to answer many of these questions.

Fish Species Studied[2/]

To meet the immediate study needs, the Biological Effects Report and studies center upon the fish of commercial and sports value in the Columbia system, particularly the Pacific salmon. The Columbia River is inhabited by four species of Pacific salmon: sockeye salmon, chum salmon, coho salmon, and chinook salmon. The chinook salmon has distinct spring, summer, and fall races, while the other species do not. Another significant anadromous member of the salmonid family is the steelhead trout, which has both summer and winter races. Other anadromous fish of the Columbia Basin include several other species of trout, smelt, and American shad.

As anadromous species, these fish seek out Columbia system waters far inland from the Pacific Ocean, historically reaching as far as Canada. They may presently be found in nearly all accessible tributaries where water quality conditions allow. Figure 1 shows the areas which remain accessible to anadromous fish since construction of the system of dams and reservoirs on the river. The area of concern for these studies was limited to the main stem, which is important principally as the migration route to all available spawning ground in the Basin and for seaward migration to the Pacific Ocean. Spawning also occurs in the only remaining unimpounded waters of the main-stem Columbia, the fifty-mile reach below Priest Rapids dam, which produces large numbers of chinook salmon.

2/ Scientific names of fish and other organisms mentioned in this report are listed in Appendix C.

The size of the Columbia River fish resource is most easily described in terms of the fish count over Bonneville Dam. In addition, it should be remembered that the Willamette River, Cowlitz River and smaller tributaries produce significant additional numbers of fish, and that the commercial and sports catch of these fish in the River and Pacific Ocean from Alaska to California should be added to the Bonneville count. The thirty-one year record of fish passing over Bonneville Dam gives an annual average count of 705,875 salmon and steelhead of all species. The populations of the various species can be summarized as shown in the following table. The total numbers of fish entering the Columbia River in recent years is considered by fisheries agencies to be as high as in the 1930's. However, the size of the fish resource is now largely dependent upon artificial production. Also, the distribution of species and races making up the total has been changed by man's alteration of the river system.

AVERAGE ANNUAL FISH COUNTS AT BONNEVILLE DAM BY SPECIES
1938-1968

Chinook salmon	385,252
Sockeye salmon	100,777
Coho salmon (Three-year average 1965-1968)	77,289
Chum salmon	1,214
Steelhead trout	141,343

Source: Annual Fish Passage Report, Columbia River Project, U. S. Army, Corps of Engineers, North Pacific Division, Portland, Oregon.

All of the salmonids have similar life histories or cycles, but each species and race matures at different rates, presenting differences in the duration and time of occurrence for the various stages of activity: spawning and incubation, rearing, juvenile migration, growth at sea, and adult migration. For example, salmon fry spend from a few weeks to over a year in fresh water before beginning seaward migration, depending upon the species and race. Similarly, the amount of time spent at sea also varies from less than one year for jack salmon[3/] to over five years, depending upon the species and race of fish. Figure 2 illustrates the time of occurrence during the year of the various stages of activity for the chinook, coho, and sockeye salmon, and for steelhead trout. As can be seen, migrating adults or juveniles can be found in the Columbia River throughout the entire year. (See also Figure 6.)

The Physical Environment

The Columbia River remains accessible to anadromous fish as far as Chief Joseph Dam, river mile (RM) 545. Throughout this length, two reaches are unimpounded: the estuary to Bonneville Dam (RM 145) and the Hanford reach between the head of McNary Pool (RM 347) and Priest Rapids Dam (RM 397). The remainder of the river is impounded behind nine run-of-the-river dams, with shallow reservoirs ranging from 54 to 165 feet in depth (Figure 1).

3/ Jack salmon are sexually precocious males.

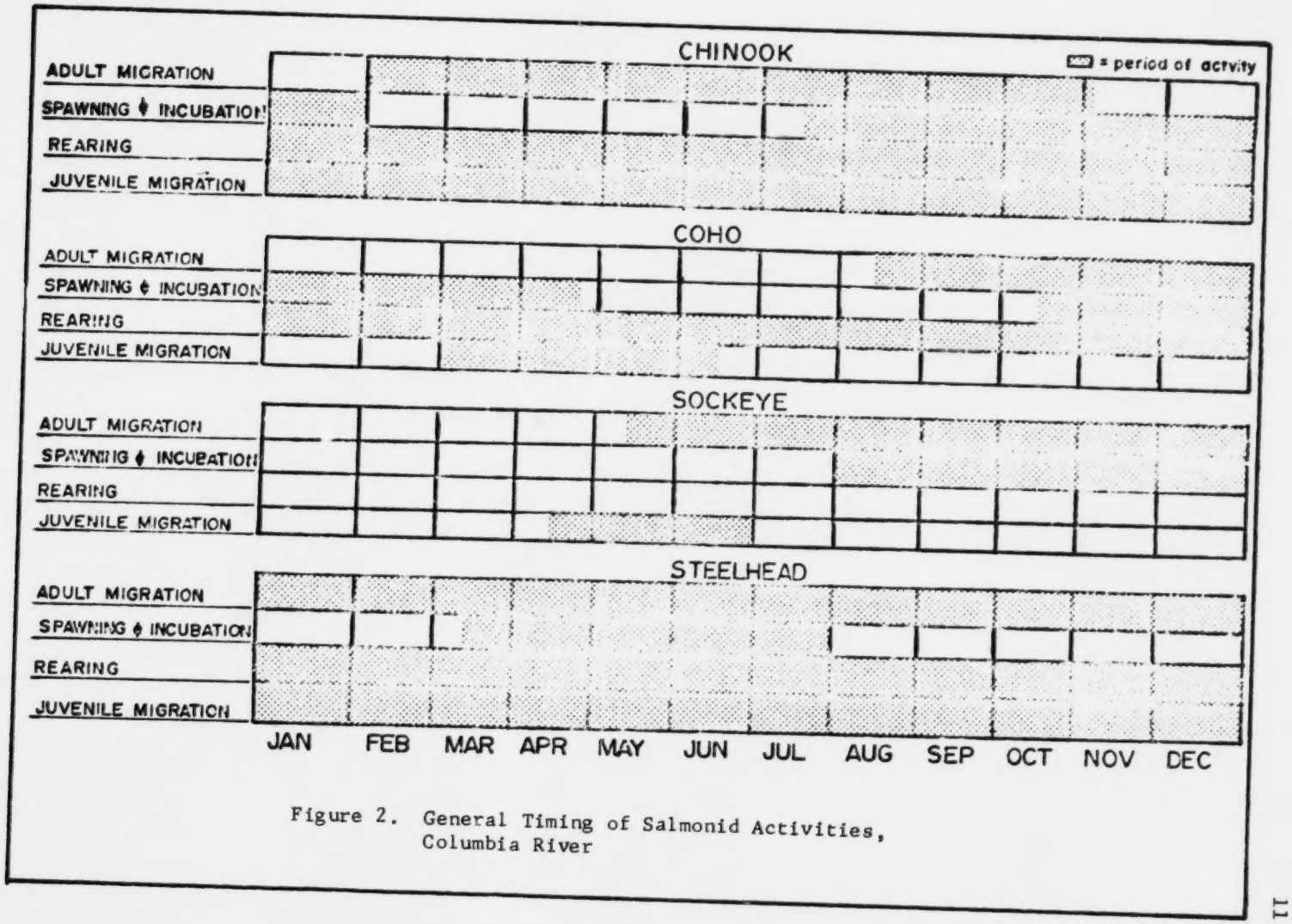

Figure 2. General Timing of Salmonid Activities, Columbia River

Flow reversals in the tidal reach of the Columbia River are common at least as far upstream as Prescott (RM 72.8) and occur most frequently during the minimum flow period, August to October (Battelle Northwest, anon 1969; Snyder and McConnell, ms 21)[4/]. The effect of a flow reversal is to accumulate effluents which may be adverse to fish.

The surface runoff in the Columbia Basin is characterized by a typical snowmelt regime, with low flows during the late summer and winter and high flows during the spring and early summer. The volume of runoff in the Columbia ranks it as the fourth largest in the North American Continent; the average annual runoff at The Dalles, Oregon is 140 million acre-feet. Mean annual flow is 195,400 cubic feet per second (cfs); mean monthly discharges range from 95,700 cfs in January to 494,700 cfs in June.

With minor exceptions, the water quality of the Columbia River--other than temperature and dissolved nitrogen--is not considered detrimental to the fish resources. Water temperatures in the main stem Columbia River to Priest Rapids Dam range from maximums in the 70's during warm summer months to lows in the 40's and occasionally in the 30's during winter. Figure 3 shows water temperature and discharge profiles for various points on the Columbia River to illustrate general temperature and flow conditions.

4/ To enable the reader to determine whether a reference in the text pertains to a study done in the CRTES or to other work, manuscripts prepared as part of the CRTES are referred to by author's name and a manuscript number which is listed in Appendix A.

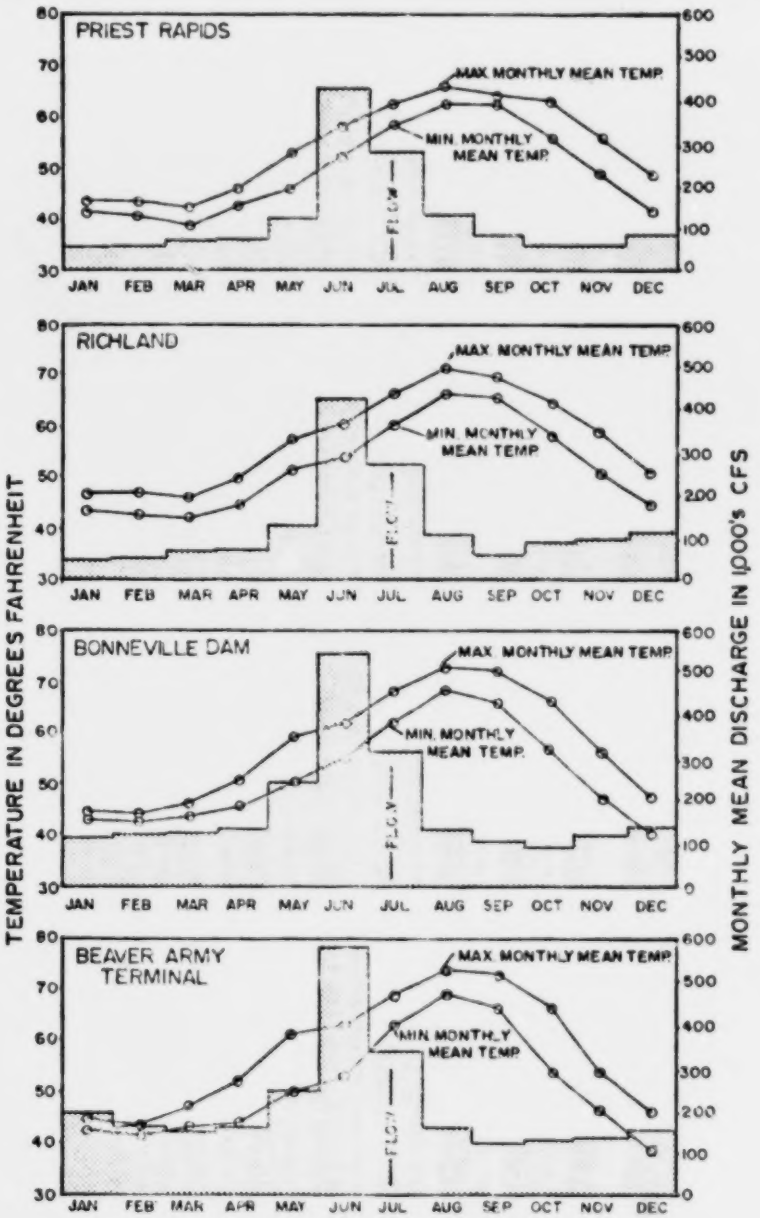

Figure 3. Temperature-Flow Profiles of Columbia River, 1967

Changes in the temperature regime of the Columbia River in terms of time of occurrence of seasonal temperature shifts and location of temperature peaks have been noted. Analysis by the U. S. Geological Survey of temperature data at Bonneville Dam in the period 1938 to 1966 indicates that a man-caused increase in Columbia River temperatures has occurred beginning in the mid-1950's (Moore, 1968). Other studies by Jaske and Goebel (1967) and Davidson (1969) have reported changes in the natural temperature regime in the Columbia River main stem, with the most significant changes being above the confluence of the Columbia and Snake Rivers. The principal effect has been the shifting of water temperature maximums so that they occur later in the year. The shift in seasonal temperature pattern has been attributed to the construction of numerous dams in the Basin. The Hanford works is one of the largest identifiable sources of advective heat on the Columbia River.

Potential for further modification of the temperature regime of the river is offered by proposals for construction of a third powerhouse at Grand Coulee Dam, additional storage in the Columbia River treaty dams, proposals to construct Ben Franklin Dam to impound the Hanford reach of the Columbia, effects of power peaking, and the potential for numerous small thermal discharges accompanying the economic growth predicted for the Region. Use of the Columbia system of reservoir releases for temperature management has been demonstrated by cooperative use of the Grand Coulee release program to lower Hanford water intake temperatures (Jaske, 1966). The use of

mathematical models for temperature prediction in the Columbia River offers potential for developing limited temperature enhancement by the water management system. The AEC simulation model COL HEAT is reported by Jaske (op. cit.). The temperature prediction capability developed by the EPA as a part of the Thermal Effects Study is presented in Volume Two.

II - SUMMARY OF CONCLUSIONS

This summary presents the generalized conclusions drawn from studies described in the literature and those conducted as part of the CRTES.

General

Many variables influence the thermal tolerance of Pacific salmon. However, within broad ranges, the fisheries agencies of the Pacific Northwest have recommended optimum temperatures which are conducive to the production of fish resources in the Columbia Basin. These ranges are:

Migration routes:	45 to 60 F (7.2 to 15.6 C)
Spawning areas:	45 to 55 F (7.2 to 12.8 C)
Rearing areas:	50 to 60 F (10 to 15.6 C)

Individual races of salmonids may have adapted to a wider range of temperatures and other factors may ultimately affect the optimum range. Nevertheless, these temperature ranges remain accepted as the most desirable conditions which can be considered conducive to enhancement of the fish resources of the Columbia Basin.

Adult Anadromous Fish

There is an increasing tendency for adult salmon and steelhead trout to cease upstream migration at temperatures of 70 F (21.1 C) and above. Existing evidence is not conclusive on whether migration would be blocked or curtailed at temperatures below that level.

Adult salmon and steelhead appear to have specific rather than random migration routes and prefer to be close to the shoreline in shallow water.

The frequency of infection from fish diseases endemic to the Columbia River increases with increasing temperatures. Temperature is but one of the stresses which may interact to instigate the effects of disease organisms. Warm water infectious diseases are less likely to cause mortalities at temperatures below 60 F (15.5 C).

Under conditions of nitrogen supersaturation, any temperature rise increases the chance of producing gas bubble disease in salmon and steelhead. Fish stressed by nitrogen supersaturation are more susceptible to the effects of thermal stress and infectious diseases.

Laboratory experiments have shown that water temperatures at 69.8 F (21 C) and above are considered to be directly lethal to more than half of adult salmon and steelhead exposed to that level; that is, temperature alone would kill the fish at that level. However, the effects of temperature in combination with other stresses (disease, nitrogen supersaturation, etc.) can be considered more important than direct temperature effects in terms of ultimate fish survival.

The discharge of heated effluents from the Hanford Atomic Works has not been demonstrated to have a detrimental effect on salmon spawning downstream or upon migrating adults.

Temperature stresses placed upon adult salmon and steelhead may indirectly and adversely affect reproduction through excess energy costs, disease, and increased toxicity

The initial egg incubation period is critically sensitive to temperature, and requires a range of 42 to 61 F (5.5 to 16.1 C) although a lower upper limit is preferable for general application.

Diurnal temperature fluctuation at temperature levels within the range 42 to 65 F (5.5 to 18.3 C) is of significant benefit to the growth and survival of eggs and fry--as opposed to constant temperature levels.

Juvenile Anadromous Fish

The growth of juvenile salmonids is enhanced at temperatures within the range of 41 to 62.6 F (5 to 17 C). Heat additions to colder waters which would bring the water temperatures within this range might be considered beneficial, while heat additions which would result in temperatures above this range would be considered detrimental to juvenile growth. The optimum temperature for growth changes with seasons and depends on food availability.

The timing of juvenile downstream migration has been significantly delayed due to impoundment by dams; the delay has many adverse effects on the fish, including subjection to unfavorable temperatures. Fall chinook produced in the Hanford reach apparently maintain their historical migration pattern (March until mid-June) from that point, although their fate downstream has not been determined. The period of peak outmigration for all species in the lower Columbia River is from March to June, with smaller numbers moving throughout the year.

The smaller juveniles migrate closer to shore, while some larger fish and selected species are found more evenly distributed throughout the stream or in mid-channel.

Based on Hanford area research, the number of downstream juvenile migrants affected by the Hanford thermal plumes is probably small. The risk of a directly lethal dose is also small, due to the velocity of the stream and rapid mixing.

In defining the thermal resistance of juvenile salmonids, the principles of thermal dose and acclimation apply: the effect of rapid temperature increase is directly proportional to duration of exposure. Acclimation to higher temperatures within the tolerance zone significantly increases thermal resistance. Fish stressed by nitrogen supersaturation, toxicants, or disease have reduced temperature resistance.

The upper allowable temperature for any species of juvenile salmonid should be a minimum of 5.4 deg. F (3 deg. C)[5/] below the ultimate upper lethal temperature to avoid significant curtailment of activity. Temperatures above 68 F (20 C) are considered to be adverse for juvenile salmonids. Temperatures near 62.6 F (17 C) may be considered to be at the upper end of the optimum temperature range. Between 62.6 and 68 F (17 and 20 C), any increase in temperature probably is of little benefit to juvenile salmonids and increases the likelihood of disease infection and other indirect effects.

5/ To distinguish between temperature changes and actual degrees of temperature, "15 deg. C" means a temperature change by that amount from some base temperature; "15 C" refers to exact temperature on a temperature scale.

Under controlled laboratory conditions, predators were shown to selectively prey upon fish whose behavior has been altered by temperature stress as compared to unstressed control fish.

Nitrogen supersaturation in the river is a significant detrimental factor weighing against successful downstream migration of juveniles, and the degree of supersaturation is accentuated by temperature increases. At nitrogen saturation levels over 115 percent, any increase in temperature could be damaging due to temperature-gas solubility relationships.

Non-Salmonid Fish

Columbia River smelt have a lower temperature preference than salmonids. The adult females may be more susceptible to detrimental effects of temperature than other fish.

Yellow perch and three-spine stickleback have a higher thermal tolerance than salmonids; however, they require a chill period.

Secondary Production Organisms

Aquatic insects form a major part of the diet of chinook fry in the Hanford reach of the Columbia River and of all salmonid species migrating through the Lower Columbia in spring and fall months. Zooplankton are the dominant food organisms from July through October in the lower river.

The most abundant plankter (*Daphnia pulex*), which is an important salmon food in the Lower Columbia River, is relatively resistant to thermal shock (30 C for 15 minutes). Below the Hanford

discharges, the maturity of an aquatic insect (Caddis fly) was advanced two weeks due to a temperature increase of about 1 deg. C. No changes in the growth pattern could be observed in another bottom invertebrate, the Columbia River limpet.

III - GENERAL CONSIDERATIONS

A discussion of the general effects of temperature on aquatic life is presented in this chapter; that is, those concepts of thermal effects which transcend the discussions of various life stages in the following chapters. The material developed here will establish a framework of definitions and concepts which will make succeeding chapters more understandable.

The significance of water temperatures to aquatic life is better understood if it is remembered that fish are cold-blooded; they depend upon their environment to provide a livable temperature range to allow their normal life functions without internal bodily regulation. The extent of influence of temperatures upon the fish has been described by Brett (1956).

> Temperature sets lethal limits to life; it conditions the animal through acclimation to meet levels of temperature that would otherwise be intolerable; it governs the rate of development; it sets the limits of metabolic rate within which the animal is free to perform; and it acts as a directive factor resulting in the congregation of fish within given thermal ranges or movements to new environmental conditions.

In the evolution of the species, the Pacific salmon and steelhead trout have adapted their life activities to the naturally occurring conditions in the Columbia Basin, so that the flow and water quality (including temperature) characteristics of the Columbia River and its tributaries, or even small creeks, have become the environmental requirements for particular species and races of salmon and steelhead.

The anadromous fish exhibit a more complex pattern of life activities than do resident fish that do not migrate. In their unique

journey from the inland spawning ground downstream to the Pacific and their return, years later, to spawn and die, the salmonids must adapt to a variety of environmental changes and stresses. Their migratory nature takes them from the clear and cold creeks with relatively small volume into the mighty Columbia and finally into the saline estuary and Pacific Ocean. The adaptatior from fresh to salt water alone is a physiological strain.

Thus, it should be remembered that, while temperature can be a stress in itself, it may be of more importance to the survival of the fish species as a synergistic agent, an influence upon the successful adaptation to other water quality and physical changes which the fish must face to fulfill their migratory instincts. Temperature influences the levels of dissolved oxygen and nitrogen in the water, the incidence of disease in the fish, their susceptibility to predation, as well as directly affecting their ability to migrate, spawn, and develop. Thus, temperatures which may be within the thermal tolerance zone, i.e., the temperatures " . . . at which the animal will never die from the effects of temperature alone" (Fry, 1947), can profoundly influence the impact of other environmental factors upon the productivity of the fish resources.

The thermal requirements and tolerances of Pacific salmon and steelhead cannot be precisely defined except in terms of several variables: the species and race of fish, the stage of development, previous or concurrent exposure to factors which interact synergistically with temperature (e.g., disease, toxicity, nitrogen supersaturation), previous acclimation temperatures, and duration as well as degree of

exposure to a given temperature. The graphic generalization presented in Figure 4 (Brett, 1960) depicts the concepts employed by biologists in defining the thermal requirements of Pacific salmon. As can be seen, the tolerance zone of temperatures which are conducive to reproduction is narrower than the range of temperatures necessary for growth of the fish. Outside the tolerance zone, the resistance of the fish to lethal temperatures (represented by the undulating line) is dependent upon several factors mentioned above.

An important concept defining the resistance of fish to lethal temperatures is acclimation. Fish acclimated to higher temperatures within the tolerance zone are most resistant to temperatures above that zone. In other words, acclimation of a fish to a warm tolerance temperature will result in a higher lethal limit for that fish, and vice versa. The influence of acclimation on thermal tolerance can be seen in Figure 5. (For purposes of comparability among investigators, the incipient lethal temperatures are generally defined as the levels at which fifty percent of the test population would die.) As can be seen from the figure, the upper level of the tolerance zone rises as the temperature to which the fish has been acclimated rises. However, in all cases there is an ultimate level at which the influence of acclimation gives way and the temperatures become lethal regardless of previous acclimation. This level is termed the ultimate incipient lethal temperature. The diagonal line in Figure 5 is a reference line to provide a ready indication of where the lethal temperature and the acclimation temperature are the same.

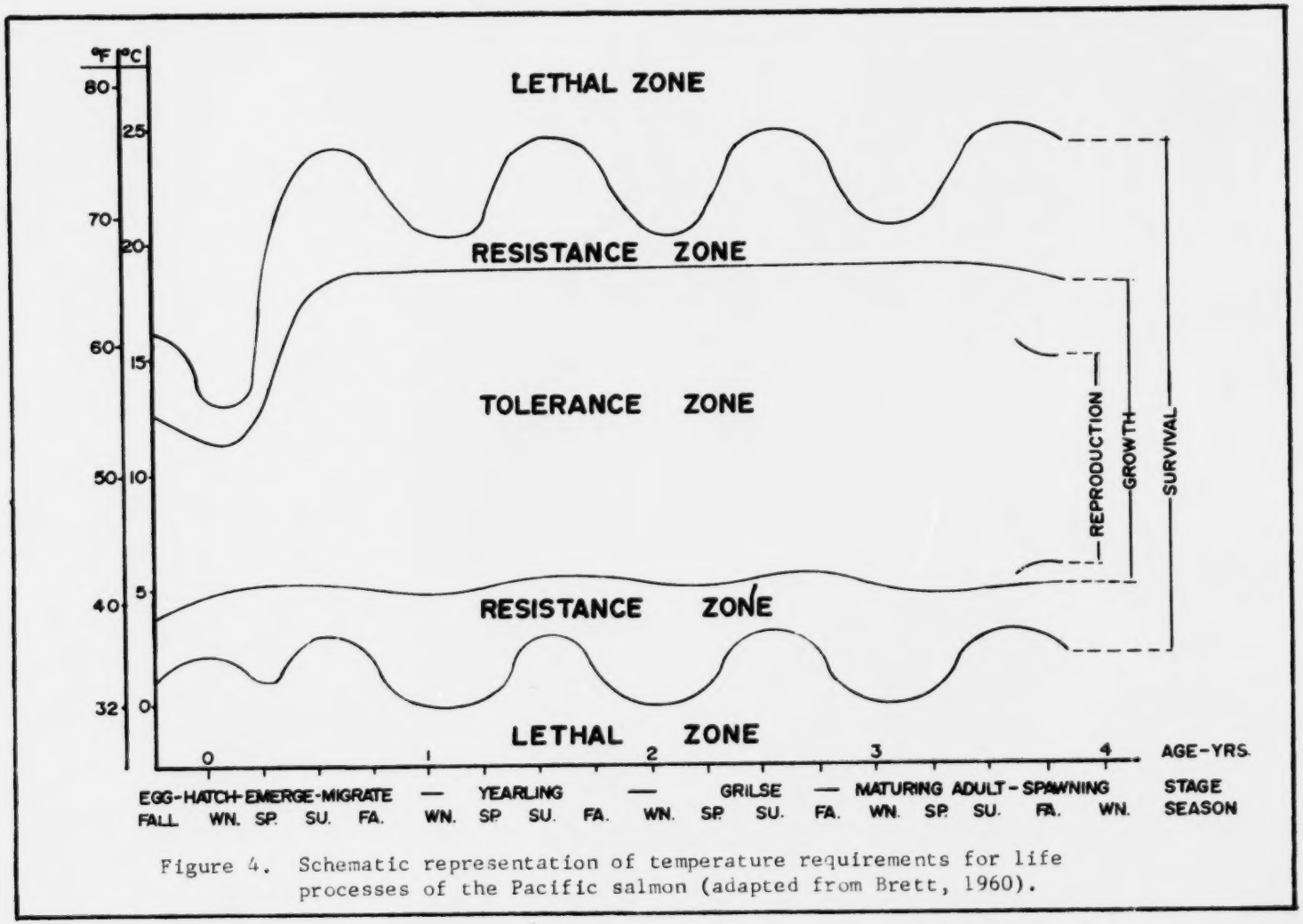

Figure 4. Schematic representation of temperature requirements for life processes of the Pacific salmon (adapted from Brett, 1960).

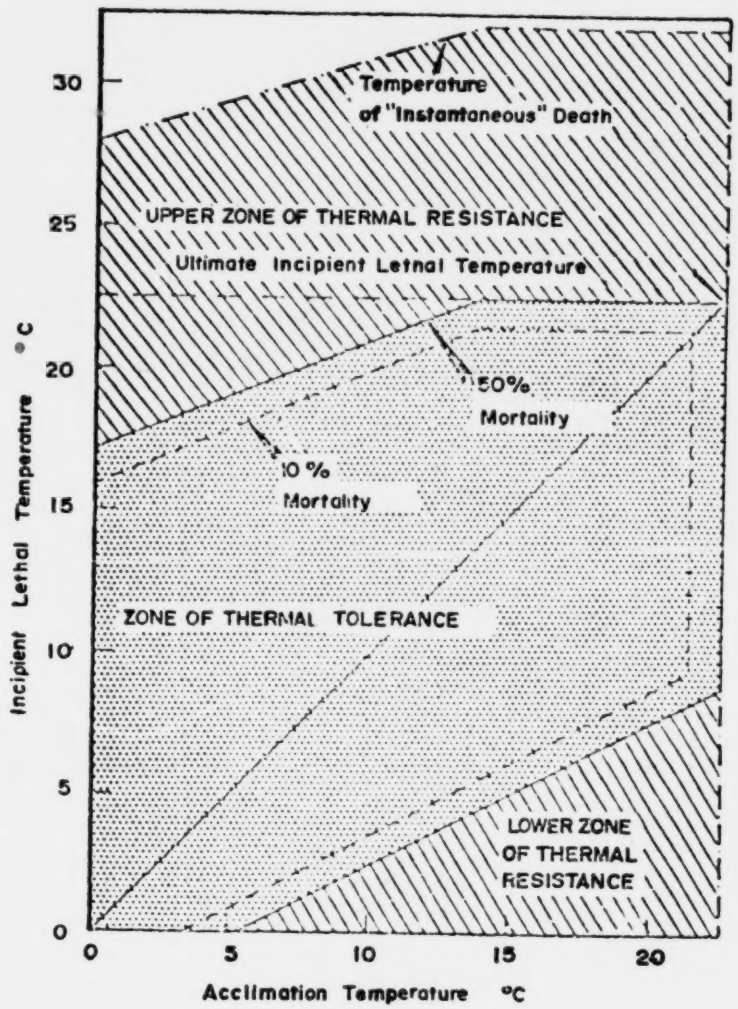

Figure 5. Thermal response of a hypothetical cold water fish (adapted from Brett, 1960, by Coutant, 1968).

The levels of temperature which will be lethal to a fish are further influenced by the time of exposure. The resistance to an abrupt increase in temperature is a function of both the degree of temperature rise and the time of exposure to that temperature--referred to as the thermal dose. Exposure to a lethal temperature for a sublethal time will not result in fish death.

The fisheries agencies of the Pacific Northwest recognize the influences of these many variables upon the thermal tolerance of Pacific salmon. Within broad ranges, however, a committee of these agencies has recommended optimum temperatures which are conducive to the production of fish resources in the Columbia Basin (Snyder et al., 1966).

Migration routes:	45 to 60 F (7.2 to 15.6 C)
Spawning areas:	45 to 55 F (7.2 to 12.8 C)
Rearing areas:	50 to 60 F (10 to 15.6 C)

The committee developed their recommendations after considering natural temperatures for fish activities throughout the basin, as well as at fish hatcheries where temperature problems have developed.

The technical committee's recommendations reinforced the work of Burrows (1963) in which he similarly defined the optimum temperatures for Pacific salmon, with one added stage. During egg and fry incubation, after the 128-cell stage of development is reached, Burrows concluded that temperature ranges may vary but should remain within 32 and 55 F (0 and 12.8 C). The effect of fry size and time of migration on survival in different areas makes it impossible to define the optimum temperature range during this stage more precisely.

Although individual races of salmonids may have adapted to a wider range of temperatures and other factors may ultimately affect the optimum range, these recommended temperatures remain accepted by the fishery agencies as the most desirable conditions which can be considered conducive to enhancement of the fish resources of the Columbia Basin. Even though temperatures which occur in the Columbia River now exceed these optimums for periods during the year, those conditions must be considered detrimental to the fish.

A number of adverse effects of existing river conditions have been noted, as will be seen in succeeding chapters. The remainder of this report concentrates primarily upon studies of the effects of temperatures outside these optimum ranges and of abrupt changes in temperature within these ranges. The optimum temperature levels and concept should be borne in mind as these studies are reviewed.

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IV - ADULT ANADROMOUS FISH

The material presented in this chapter concerns the effects of temperatures on adult anadromous fish from the time they enter the Columbia River from the Pacific Ocean to the completion of spawning in the upper reaches of the Columbia River and its tributaries. The discussion centers first upon the migration period, then turns to spawning conditions.

Adult Migration

Adult Migration Timing

Few studies have related temperature to the migration of adult anadromous fish, although a number of biologists believe there is evidence that temperature is an important factor. The timing of migration and relative abundance of adult anadromous fish at Prescott, Oregon, was developed by Coutant and Becker (1968) and is shown in figure 6. Fish counts at the dams on the Columbia River and major tributaries also show timing of migration.

Thermal Block

The question of whether increased water temperatures could create a block to inland migration of adult fish has been raised. A number of observations seemed to indicate a relationship between temperatures and migration.

In an extreme temperature year (1941), sockeye and chinook salmon and steelhead trout were observed congregating in small, hitherto unused, cold creeks near Bonneville and Rock Island Dams

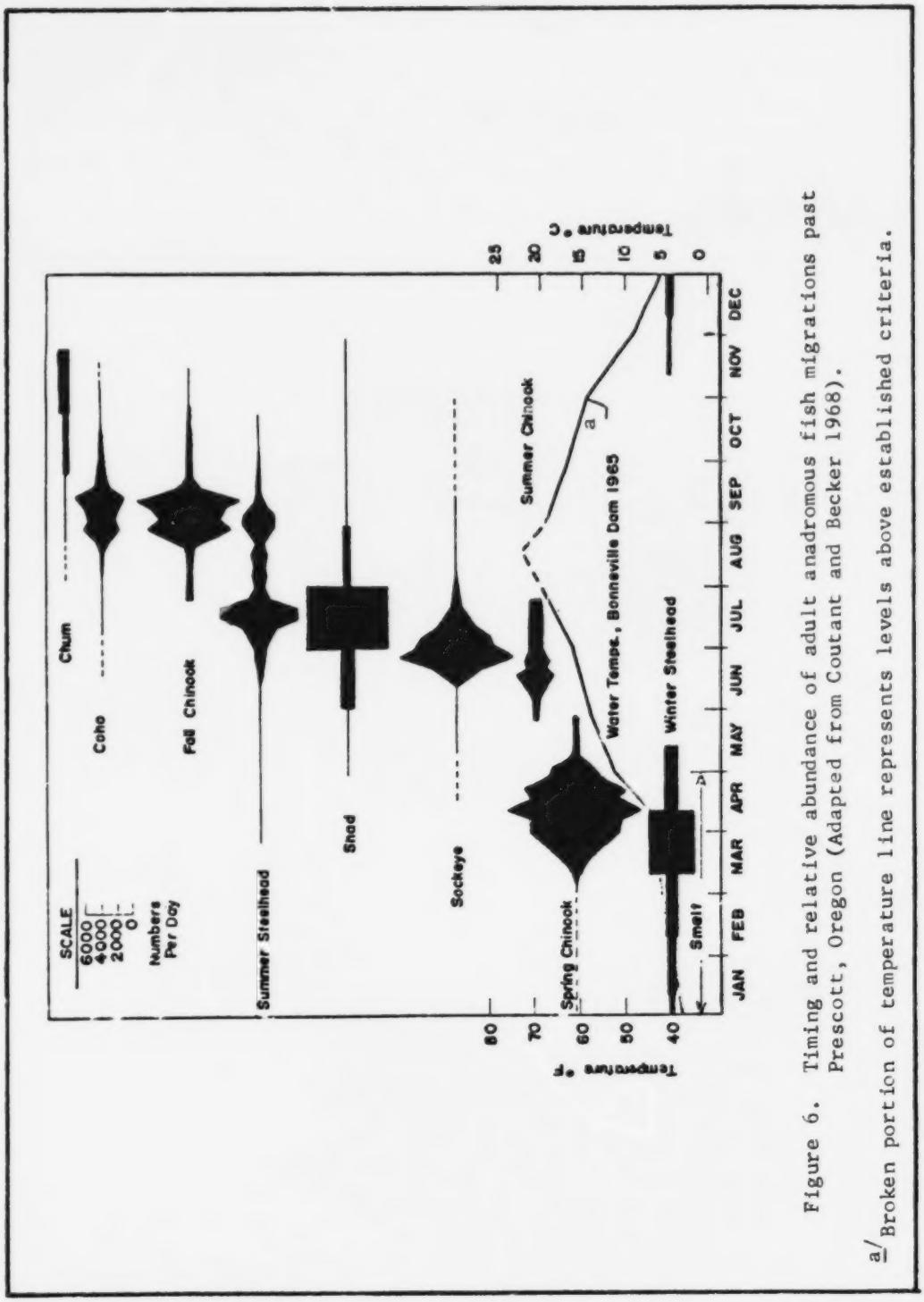

Figure 6. Timing and relative abundance of adult anadromous fish migrations past Prescott, Oregon (Adapted from Coutant and Becker 1968).

a/ Broken portion of temperature line represents levels above established criteria.

when temperatures in the Columbia rose to 71 to 75 F (21.7 to 23.9 C) (Fish and Hanavan, 1948). Similarly, high water temperature has been attributed as a major cause of delayed migration of sockeye salmon into the Okanogan River. When the Okanogan was 70 F (21.1 C) or rising above that level, the fish would not leave the cooler Columbia River to enter their natal Okanogan. Migration was resumed when the temperature began to fall. Below 70 F (21.1 C) migration was not blocked by rising or stable temperatures (Major and Mighell, 1967).

To test the influence of temperatures on the selection or avoidance of migration routes, the National Marine Fisheries Service conducted tests at the Fisheries Engineering Research Laboratory at Bonneville Dam. Although the results were not conclusive in defining the existence of a temperature block, the adult salmon and steelhead did show a preference for ambient or cooler temperatures over migration channels whose waters were above 70 F (21.1 C). No preference or avoidance of either cooler or warmer waters was shown as long as the ambient water temperatures remained between 50 and 70 F (10 to 21.1 C) (Anon, 1965-1968).

It has been speculated that large thermal discharges to the Columbia might cause a thermal block similar to that noted above for natural situations. Tracking sonic tagged steelhead trout and summer chinook salmon at Hanford has shown no such block, however, at that location (Coutant, MS 35). Fish apparently avoided the warmest areas of the river and travelled through the section essentially unimpeded. There were no statistically

significant differences in migration rates between downstream reaches heated 3.6 to 5.4 deg. F (2 to 3 deg. C) above normal and the cooler upstream reaches at times when summer water temperatures remained generally below 68 F (20 C). Some fish changed course of migration when they entered shoreline seepage areas of warmed water.

From available evidence it is concluded that there is an increasing tendency for salmon and steelhead trout to cease upstream migration at temperatures of 70 F (21.1 C) and above. Existing evidence is not conclusive on whether migration would be blocked or curtailed at temperatures below that level.

Location in Stream Cross-Section

To provide a sounder basis for water quality management decisions, the question was raised whether salmon and steelhead trout exhibit a preferred location in the stream cross-section, either in distance from shore or in depth. Little data are available to relate fish location to the temperature stratification which occurs in reservoirs and the mixing and dispersion patterns of heated discharges.

Sonically-tagged adult steelhead traced upstream through Ice Harbor Reservoir during the fall of 1969 usually travelled relatively close to the reservoir shore in waters forty-feet deep or less. The fish followed a fairly specific route through the reservoir with distinct travelling, milling and resting areas.

The fish favored the bottom area during September and October but were surface oriented during November and December. The slower rate of travel through the reservoir in November and December is presumed to be due to lower water temperature (Monan, Liscom and Smith, ms 2). Other studies of migration of sonic-tagged fish in the unimpounded Hanford reach of the Columbia indicated that both steelhead tro and chinook salmon migrated principally along shorelines, in water less than 5 meters deep. Throughout the distance between Richland and Priest Rapids Dam, fish selected the north (or east) shoreline. This selection was most pronounced in the area of operating reactors which were located on the opposite shoreline. The pattern was essentially the same in two years, 1967 and 1968 (Coutant 1969). The reason for the shoreline specificity has not been determined.

Although the knowledge of migration routes in the Columbia is sparse, the available evidence indicates that adult salmon and steelhead appear to have specific rathe than random migration routes and that they prefer to be close to shoreline in shallow water.

Infectious Diseases

Three diseases endemic to the Columbia River are recognized to be the most serious to adult salmon and steelhead trout: columnaris, furunculosis and ceratomxya. The first two are bacterial diseases while the latter is due to a protozoan. High mortalities of the

adult fish prior to spawning, particularly where they are confined, e.g., a spawning channel, have been attributed to one or more of these diseases. Pathogenic agents appear to be more of a problem to adults than to juveniles during migration (Fujihara, 1968). Columnaris has been subjected to the greatest investigation, especially with regard to adult salmon. The relationship of disease incidence and severity to water temperature conditions has been demonstrated by several investigations (Ordal and Pacha, 1963).

Natural outbreaks of columnaris disease in adult salmon have been linked to high water temperatures in the Fraser River, British Columbia. Adult sockeye salmon were exposed to columnaris as they entered the river, with resident fish probably providing the source of infection. The pathological effects of the disease became evident when water temperatures along the migration route, and in spawning areas, exceeded 60 F (15.5 C).7/ Prespawning mortality reached 90 percent in some tributaries. Columnaris in the infected sockeye spawners was controlled when temperatures fell below 57-58 F (13.9-14.4 C) and mortalities were reduced (Colgrove and Wood, 1966).

In laboratory experiments using Columbia River water, adult sockeye and coho salmon were examined for columnaris infection after being held at temperature levels of 50, 62, 68, and 73 F (10, 16.7, 20, and 22.2 C). At 68 and 72 F (20, 22.2 C) dead fish frequently showed the lesions typical of columnaris infection which are sufficient to

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7/ Pathological effects is the identification of disease organisms by the technique of streaking from suspected areas of infection onto nutrient plates for incubation and examination.

account for death. Columnaris and other diseases were believed to be responsible for the death of many of these fish, although 72 F (22.2 C) was considered directly lethal to most of the adult salmon over a period of a week. Adult sockeye and coho were thoroughly exposed to columnaris disease at all temperature levels but infections failed to develop at the 50 F (10 C) level, and were not lethal at 62 F (16.7 C) (Bouck, et al., ms 1).

Other studies of the occurrence of columnaris in the Columbia River fish recognize the influence of higher temperatures on infection, but also emphasize that many factors interact to cause infection. Battelle Northwest studies in the Hanford area draw attention to the resident infection carrier:

> "The presence of immune carrier fish capable of releasing large numbers of C. columnaris organisms to the water is probably the primary cause of salmonid infection in the Columbia River. Fish ladders with high population density of coarse fishes during migration of salmonids are the most likely sites of exposure and infection (Fujihara, 1967). Since non-exposed fish appear to be very susceptible to infection, the release of heavy concentrations of the pathogen with the correspondingly low water flow in ladders would create ideal conditions for infection." (Fujihara and Nakatani, ms 43).

Data collected on antibody levels in Columbia River fish "...suggest peak yearly effective infection of at least 70 percent to 80 percent of most adult river fish species" (Fujihara and Hungate, ms 42). Occurrence of the disease was generally associated with temperatures above 55 F (12.8 C); the authors further suggest that the incidence of columnaris may be increased more by extended periods of warm temperatures than by peak summer temperatures. Incidence of columnaris was generally most severe in the Snake River and in the

Columbia River for some distance below its confluence with the Snake River. This may be due to Snake River temperatures being 1.8 to 5.4 deg. F (1-3 deg. C) higher than the Columbia River (Fujihara and Hungate ms 42).

The above studies demonstrate that certain diseases endemic to the Columbia River become more infectious with increasing temperatures. However, the disease cause and effect relationship is understood only in general terms of stress factors, one of which is temperature. Other factors including the general condition of the fish, nutritional state, size, presence of toxicants, level of antibody protection, exposure to nitrogen supersaturation, level of dissolved oxygen, and perhaps other factors interrelate in the infection of fish by diseases. However, the diseases discussed here are of less importance at temperatures below 60 F (15.5 C); that is, in most instances mortalities due to columnaris are minimized or eliminated below that level.

Gas Bubble Disease

Gas bubble disease occurs when the river water is supersaturated with dissolved nitrogen gas. The disease is characterized by the appearance of macroscopic gas bubbles under the skin or in the fins and in the blood. Early observations of this phenomenon were related to hatchery water supply systems (Rucker and Hodgeboom, 1953). The histopathology of gas bubble disease has been described as interruption of the blood supply to an organ when gas bubbles (embolism) form in the blood vessels. An embolism reaching the heart can cause death (Pauley and Nakatani, 1967; Bouck, et al., 1970).

Nitrogen supersaturation has been recognized as a critical problem in the Columbia River and, during severe periods, essentially all impounded areas and certain free flowing sections of the Columbia and Snake Rivers which are accessible to salmon and steelhead are significantly supersaturated. The condition occurs when the release of water over the spillways at dams forces the normal nitrogen levels (100 percent equilibrium with air) to rise to supersaturation.

Some reduction in dissolved nitrogen levels would result from passage of more water through turbines and less over the spillway. Investigations into possible methods of reducing spill at the dams on the Columbia and Snake Rivers and consideration of other methods for controlling nitrogen leave little hope for a significant reduction of the problem in the near future.

During the fall and winter, water is generally not spilled over the dams and nitrogen saturation levels are normal; during the spring and summer, spilling from the dams causes nitrogen supersaturation of 120 to 146 percent (Ebel, 1969; Ebel, 1970, A and B).

The harmful effects of high water temperatures on adult salmon are worsened by prior or simultaneous exposure to nitrogen supersaturation. Survival time of jack chinook acclimated to 62.6 F (17 C) which were subjected to 71.6 water (22 C) was drastically shortened when the warmer water contained dissolved nitrogen gas levels in excess of 115 percent of saturation (Coutant and Genoway, 1968). Acclimation of the fish to water supersaturated with nitrogen reduced subsequent survival time at 71.6 F (22 C), regardless of the nitrogen levels in the warmer water.

During a period of high nitrogen supersaturation in the Columbia River, adult sockeye salmon were removed from the river and subjected to air equilibrated water at temperatures varying between 50 and 72 F (10-22.2 C). Loss of eyes or blindness, which was attributed to gas bubble disease, occurred in a third of the fish at the 50 and 62 F levels (10-16.7 C), but increased to one-half to two-thirds of the fish when temperatures were 68 and 72 F, respectively (20, 22.2 C) (Bouck, et al., ms 1).

The scope and exact nature of this nitrogen-temperature interaction in fish is not well understood; however, sufficient evidence exists to warrant the conclusion that any temperature increase intensifies harmful effects of gas bubble disease, primarily due to temperature-gas solubility relationships. Further, fish stressed by nitrogen supersaturation are more susceptible to the effects of thermal stress and infectious diseases (Bouck, et al., op cit.). Although the full impact of nitrogen supersaturation upon fish is not completely understood, evidence indicates that the condition results in significant mortality of both adult and juvenile salmon and steelhead. In addition, the disease can cause sub-lethal damage, such as blindness, which may be essentially equivalent to death in terms of damage to natural reproductive potential (Westgard, 1964; Bouck, et al., ms 1).

Adult Thermal Resistance

For the purposes of this report, the concept of thermal resistance refers to the resistance of fish to temperature levels

outside their preferred or optimum range, and to abrupt changes in temperature within that range.

The precise temperature level which would cause direct thermal death to adult Pacific salmon has not been defined, due in part to the difficulties in testing such large animals. The physiological causes of direct thermal death to fish are still unknown, but are presumed to involve a complex disruption of the cellular processes by purely thermal (physical) means. One hypothesis suggests that oxygen delivery to the nervous tissue lags behind metabolic usage at the lethal temperature. In one study, 69.8 F (21 C) was estimated to be near the ultimate incipient lethal temperature for adult coho (Coutant, ms 38). (The incipient lethal level of water temperatures in these studies was defined as the level at which fifty percent of the animals died but the remainder survived for an indefinite period of time.) For steelhead, the incipient lethal level was estimated to be near 69.8 F (21 C), and for chinook, near 69.8-71.6 F (21-22 C) (Coutant, op. cit.). These studies "...suggest that elevation of general environmental temperatures above 21 C would be directly lethal to adult salmon and steelhead" (Coutant, op. cit.).

In other studies designed to determine the effects of temperature during simulated migration of adult sockeye salmon, (Bouck, et al., ms 1) the fish were subjected to four temperature levels:

a. 50 F (10 C), a theoretical optimum temperature;
b. 62 F (16.5C), Columbia River temperature on July 1, 1969;
c. 68 F (20 C), Columbia River legal temperature limit;
d. 72 F (22 C), an estimated directly lethal temperature.

In these studies, adult sockeye salmon survived an average of 3.2 days at 72 F (22.2 C) and 11.7 days at 68 F (20 C). Because of the sudden onset and rate of mortality, 72 F (22.2 C) was considered to be directly and acutely lethal to adult sockeye salmon. Survival of a few adult sockeye salmon for about one month indicated that 68 F (20 C) is not directly lethal.

However, as will be emphasized throughout this report, the effects of temperatures in conjunction with other stresses is equally or more important than direct lethal effects in terms of ultimate fish survival. For example, in the studies above, 68 F (20 C) was not considered an ultimately safe level for adult sockeye salmon because the effects of other stresses such as gas bubble disease and infectious diseases were aggravated at that temperature. The added stress of holding the fish was no doubt an additional factor.

Spawning

Effects of Temperature on Spawning

The effects of water temperatures upon salmon spawning have not been well defined in the literature, although the preferred range is considered to be similar to that for egg incubation, 42-55 F (5.5-12.8 C). The range reported by the Columbia River Fishery Technical Committee for spawning of all species in the Columbia River tributaries is 34-67 F (1.1-19.4 C) (Snyder, et al., 1966).

Since the Hanford reach has been subjected to the possible detrimental effects of heated effluents of the atomic reactors

and is the only Columbia River main stem section remaining suitable for salmon spawning, more studies have been directed to the conditions in that area than elsewhere. Nakatani (1969) states that most of the local fall chinook spawn in water temperatures about 50-59 F (10-15 C) but the late spawners in a cold year may deposit their eggs in temperatures of about 41 F (5 C), well below the optimum.

Some of the conclusions reported by Watson (ms 39) on studies of fall chinook salmon spawning in the Hanford reach of the Columbia River over the period 1947-69 are: (1) Throughout this period, no apparent relationship existed between numbers of fall chinook salmon spawning in the Hanford reach and river temperature, flow, or elevation during the spawning season. (2) Closure of reactors immediately upstream from major spawning areas did not alter the general distribution of the spawning fish. (3) The assessment of any subtle biological effects of the reactors on local salmon populations was not possible in the study. (4) Other changes in the ecology of the river, such as produced by dams, appear to be of greater influence on the numbers of locally spawning salmon than the reactor operation.

The major spawning areas between RM 363 and RM 376 (km 585-605) lie downstream from heated effluent outfalls and have been subjected to incompletely mixed effluents. In several years, salmon spawning was observed within a hundred meters downstream from effluent outfalls, but the exact nature of the temperature profile in this

region of incompletely mixed thermal plume was not known.

A study in an area of incompletely mixed effluent during the winter of 1954-55 showed the temperature difference between water above and below the gravel surface was usually less than 1 deg. C. The distribution of spawning salmon in the river downstream from the effluent of four reactors showed little change after the reactors were no longer in operation. The location of spawning areas appears to be primarily influenced by gravel size, current velocity, and water depth (Nakatani, 1969).

Overall, these studies indicate that there is no evident relationship between the operation of the Hanford reactors and numbers of fish spawning in the Hanford reach of the river.

Ability to Spawn Volitionally

The effect, if any, of water temperatures upon the ability of the salmon to spawn has been subjected to only limited study. Information gained by Bouck et al. (ms 1) in adult salmon studies at Bonneville showed no apparent adverse effects to eggs in utero of coho salmon from prolonged exposure of the adult fish to 62 F (16.7 C). At 68 F (20 C), prespawning mortalities were sufficiently high to preclude judgment of temperature effects on eggs in utero. Aside from the more direct effects of disease on maturing salmon, it was observed that the increased metabolic rate at higher temperatures manifests itself in abnormal body weight loss and a corresponding decrease in weight of sex products. These changes cannot be viewed as beneficial to migration or survival of the fish to spawn.

The additional stresses placed on a fish by higher temperatures may indirectly and adversely affect reproduction in terms of excess energy costs, disease, and increased toxicity. In other words, although the exposure of the adult female to adverse temperatures may have secondary effects which cause prespawning mortalities, the detrimental effects on the eggs in utero have not been demonstrated.

Egg Incubation

Biologists concerned with hatchery production in particular have been concerned with the effects of water temperatures on salmon eggs at various stages of development. Several investigators have explored the effects of high or low temperatures on salmon egg incubation (Combs and Burrows, 1957; Combs, 1965; Olson and Foster, 1955).

In studies of embryonic development, the order of appearance of anatomical features in the embryo and certain meristic characteristics of fish were shown to be dependent on temperature of incubation (Hayes, et al., 1953; Hubbs, 1922). Premature hatching at low temperatures increases the proportion of abnormal fry produced. The number of vertebrae also depends on temperature.

Burrows (1953) found that egg and fry incubation temperatures, after the 128-cell stage of development is reached, may vary but should remain within the range of 32-55 F (0-12.8 C). A number of researchers have reached the same general conclusion: to avoid excessive mortali-

ties of eggs and resulting fry the initial egg incubation should not be at a temperature higher than 59-61 F (15-16.1 C). The Columbia Basin Fishery Technical Committee reached the following conclusions after review of the results of several investigators (Snyder, et al., 1966):

1. Differences in results of the several investigations on temperature limits for incubation of salmon eggs are not too important from a practical standpoint.

2. Temperature during initial incubation is critical.

3. If initial incubation temperature is below 42.5 F (5.8 C) or above 55 F (12.8 C) less than normal survival can be expected.

4. Mortality attributable to temperature is also a function of duration of exposure.

Experiments at Hanford in 1965 (Olson and Nakatani, 1968) showed higher mortalities in eggs incubated in cold river water than in lots incubated in water warmed by addition of reactor effluent. Nakatani (1969) believes that warming the colder waters of the Columbia River in early winter might actually be beneficial for egg incubation.

From the many studies of egg incubation and temperatures, it is generally agreed that the initial egg incubation temperature is critical and should be within the range of 42-55 F (5.5-12.8 C) and should remain below 58 F (14.4 C) at all times but may go as low as 32 F (0 C) after the 128-cell stage.

Importance of Natural Temperature Fluctuation

Many of the laboratory studies to define the necessary temperature range for egg incubation were conducted at controlled constant temperature levels. Since natural temperatures in the stream fluctuate daily under the influence of solar radiation, the significance of fluctuating temperatures should also be noted, although studies of this aspect of egg incubation have been limited.

Olson and Nakatani (ms 45) investigated the effect of fluctuating temperatures on incubating chinook salmon eggs and fry at increments ranging 1, 2, and 3 deg. F above and below the basic river temperature. No difference in survival was found as compared to nonoscillating temperatures.

The Oregon Fish Commission and National Marine Fisheries Service in 1969 cooperated on experimental incubation of fall chinook eggs (Fulton, unpublished manuscript). On a simulated natural diurnal temperature regime, peak temperatures were from 60 to 65 F (15.5-18.3 C) with a 4 deg. F fluctuation. The results in both constant and fluctuated temperature groups generally agreed with other investigators; that is, above the optimum range the warmer the water, the lower the egg survival. However, there was a significantly greater survival in eggs incubated at fluctuating temperatures with peaks above 63 F (17.2 C) and a significantly better survival for fry at all temperatures (with one exception) in the fluctuated temperature group when compared with constant temperature groups. This indicates that there may be significant benefit to eggs and fry from a diurnal temperature fluctuation at all levels within the zone of tolerance 42 to 65 F (5.5 to 18.3 C).

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V - JUVENILE ANADROMOUS FISH

The temperature requirements and tolerances of juvenile anadromous fish, from the fry stage through seaward migration to the Pacific Ocean, is the subject of this chapter. The discussion centers first on the rearing stage in fresh water, a period which may vary from one week to over a year depending upon the fish species and race. Juvenile migration to the sea is then discussed in terms of temperature effects.

Rearing

Growth Rate of Juvenile Salmonids

Two aspects of the relationship between juvenile growth and water temperatures require attention. First, the effect of incremental increases in water temperature over natural conditions should be known; and second, the desirable range of temperatures for enhancement of juvenile growth should be defined.

The effect of incremental increases in temperature over the Columbia River seasonal pattern has been observed on young salmon and trout (Olson and Foster, 1955; Olson and Nakatani, 1968). Increased water temperatures clearly accelerated fish growth in all lots. Fish in the warmest lots were as much as eight times heavier than those in the coldest lots at the conclusion of the tests. Excessive mortalities resulted from temperature increases in excess of 4 deg. F over the river temperature for the lots spawned on October 30; but an incremental increase of 12.5 deg. F over the base temperature for

lots spawned on December 8 produced a mortality of only 12.4 percent. The significance appears to be that 4 deg. F over the October 30 temperature results in the water being over 60 F, while 12.5 deg. F added to the December 8 temperature produces 60 F or below. The researchers believe their studies indicate that young fall chinooks can safely withstand greater thermal additions during the winter and suggest, further, that elevated temperatures will favor the survival of the eggs spawned in the colder late months of the year over those spawned earlier.

In other studies the effect of incremental increases of 2, 4, and 4.7 deg. F (1.7, 2.2, and 2.6 deg. C) above Columbia River temperatures was tested on the growth of juvenile steelhead (Olson and Templeton, ms 46). The warmest of these heat increments tended to slow the rate of growth when added to summer maximum temperature waters (average of 70 F, 21.1 C) but favored the growth during the colder seasons of the year.

Brett et al. (1969) studied growth of fingerling sockeye salmon in relation to water temperature and the metabolic rate of food utilization. The most favorable range for growth was found to be between 41 and 62.6 F (5-17 C), with a physiological optimum in the vicinity of 59 F (15 C). The amount of food necessary to maintain the fishes weight increased rapidly as temperatures rose above 53.6 F (12 C), with no growth occurring at approximately 73.4 F (23 C), despite the presence of excess food.

In field and lab studies with juvenile coho at Oregon State University, Averett (1969) found that the range of temperatures at which maximum efficiency of food utilization for growth appears, changes with season and depends upon the range of consumption rates being considered within a season. His findings show the most efficient growth, within consumption ranges believed to occur in nature, is at the temperature of 41 to 57.2 F (5 to 14 C) in early spring, 51.8 to 57.2 F (11 to 14 C) in early summer, 57.2 to 62.6 F (14 to 17 C) in late summer, 51.8 to 62.6 F (11 to 17 C) in fall, and 41 to 46.4 F (5 to 8 C) in late winter.

Additional laboratory studies, also at Oregon State University, compared growth rates of juvenile coho salmon kept at different fluctuating temperatures (L. B. Everson, MS Thesis). Temperatures were incrementally increased approximately 6.3 and 12.6 deg. F (3.5 and 7.0 deg C) from control temperatures that followed the daily and seasonal temperature changes of a natural stream. Relationships were established between rates of food consumption and growth during short-term (30 day) and long-term (8 month) studies. At comparable ration sizes the growth rates of fish kept at elevated temperatures were generally lower than those kept at control temperatures. The response to elevated temperature was markedly influenced by ration size; the greater the ration, the more nearly were growth rates comparable at all temperatures studied. Comparison of results of short and long-term studies indicated that the fish did not benefit from long-term acclimation to elevated temperatures. Seasonal

differences in food consumption, and consequently growth, that are not directly related to temperature are indicated from comparison of results obtained during different seasons but over similar ranges of temperature.

Studies with juvenile coho salmon at control and elevated temperatures 9 deg. F (5 deg. C) increment in two large outdoor model streams at Oregon State University have shown that heating enhanced growth only during the winter of the first year of operation. Growth subsequently has been greater in the control than in the treatment stream. The level of abundance of benthic invertebrates appears to be closely related to the differences in growth of the coho (R. A. Iverson, personal communication).

Becker (ms 40) studied the food, feeding, and growth of juvenile chinook salmon at stations above and below nuclear reactor effluent discharges in the Columbia River. He found a lack of detectable thermal effects which he attributed to the fact that the thermal discharge plumes are in mid-river and the effluents are well mixed before reaching inshore feeding areas. The transient nature of the fish populations, and the availability of food organisms in the river drift complicated efforts to evaluate any subtle thermal effects.

To summarize, the growth of juvenile salmonids is enhanced at temperatures within the range 41-62.6 F (5-17 C) depending on season and availability of food. Heat additions to colder waters which would bring the water temperatures within this range might be considered beneficial, while heat additions which would result in temperatures above this range would be considered detrimental to juvenile growth.

Attraction of Juveniles to Warmed Water

During cold-water periods in the Hanford reach of the Columbia, seining in the inter-gravel seepage area near the B-C reactor showed that small numbers of chinook fry were present in the area which was warmed by the seepage to 50 to 53.6 F (10-12 C). The warming of the areas is the result of seepage from an effluent disposal ditch. No fry were available in the other areas of the river where the river temperatures during March remained at 35.6 to 39.2 F (2 to 4 C). Becker (ms 40) speculates that the young chinook select the warmer areas when the river temperature is below a lower thermal preferendum 53.6 to 57.2 F; 12 to 14 C). He postulates that, because the river temperatures in early spring are well below the preferred level for juvenile salmon, the addition of heat by the Hanford discharges during early spring is not harmful and may actually be beneficial to the emergent fry (Becker, op. cit.).

Juvenile Migration

Juvenile Migration Timing

Although the annual timing of seaward migration of juvenile salmonids varies according to species and race of fish, each does exhibit distinct timing patterns which are preferred and beneficial to successful downstream migration. Migration has historically been timed to coincide with favorable temperature and flow conditions during the year. The construction of dams and reservoirs in the Columbia system has altered the historical migration patterns.

On the Columbia and Snake Rivers, studies have been made of the time of juvenile salmonid migration under both pre- and post-impoundment conditions. Mains and Smith (1964) found that before impoundment the migration of zero-age chinook from the upper Columbia River occurred during March through July. After construction of four dams, Park (1969) found that the migration period had shifted to April through August at Priest Rapids Dam, with peak numbers in August during 1965 and 1966. However, since juvenile chinook were found by Becker (ms 41) to be in the Hanford reach of the Columbia from March until mid-June, he concluded that the progeny of fall chinook spawning in the Hanford reach retain the historical migration pattern detected by Mains and Smith (1964) above.

The migration rates of yearling chinook salmon in the Columbia and Snake Rivers were measured by Raymond (1968, 1969). Marked fish took 32 days to travel from the Salmon River to Bonneville Dam in 1966, a distance of 415.6 miles (669 km). He predicted that, with additional impoundment of the Snake River, an additional 36 days (total of 68 days) would be required for salmon to migrate from the Salmon River and Grand Ronde River to Bonneville Dam.

Park (1969) observed that the peak movement of juvenile chinook in 1966 at Bonneville Dam occurred two months later (June versus April) than in the period 1946-1953. He also indicated that the peak movement at Bonneville was influenced by the late release of many of these fish from upstream hatcheries.

From these studies, it appears the time of downstream migration

of juvenile salmonids through the upper and mid Columbia River has been significantly delayed due to impoundment of the river by dams. Migration of fall chinook produced in the Hanford reach of the Columbia appears to commence in the same period as the historical, pre-impoundment pattern--although whether delays in migration of these fish occur in reservoirs downstream has not been considered.

The effect of delays in juvenile migration is to subject the fish to increased stresses and adverse conditions. The detrimental aspects of delay in migration and of the alteration of the physical condition of the migration route into a series of reservoir environments have been described by a number of studies (Park, 1969; Davidson, 1965; and Raymond, 1970, B). Juvenile salmon and steelhead that are delayed in downstream migration may be forced to migrate during an unfavorable time period in terms of seasonal temperature rises in the Columbia River. Downstream juvenile migrants have historically migrated during periods of high flows and moderate temperature; delays in this pattern bring them into peak summer temperatures and curtailed flow conditions.

Delayed entry into salt water also is considered detrimental. Baggerman (1959) has suggested that the disposition for seaward migration of juvenile Pacific salmon is directly related to an observed salt-water preference. "Juvenile salmon exhibit a preference for salt water prior to, during, and after the normal period of downstream migration." Therefore, it has been suggested that delays in reservoirs could adversely affect production, since either premature

or delayed entry into salt water appears to reduce the survival rate (Andrew and Geen, 1960).

When delayed in the reservoir, the migrants encounter increased temperature conditions caused by seasonal warming characteristics. Several related studies support this theory. Apparently, salmonids stop their migration when they encounter a temperature gradient upon entering a reservoir from a stream (Durkin, et al., in press). Other observations at storage reservoirs are unpublished. Juvenile salmon and steelhead that are delayed may lose their desire, or even ability, to migrate and become residual in the reservoir where they are subjected to unfavorable temperature, nitrogen supersaturation, increased predation, and disease.

The relative abundance of young anadromous fish in the lower Columbia River in relation to season and temperature is discussed by Coutant and Becker (1968) and is shown in Figure 7.

The generalized conclusions relative to juvenile migration timing, are that the downstream migration from the upper and mid-Columbia has been significantly delayed due to impoundment by dams; the delay has many adverse effects on the fish, including subjection to unfavorable temperatures. Fall chinook produced in the Hanford reach apparently maintain the historical migration pattern of departure from that point. Although inconsistent with the above information, the period of peak outmigration in the lower Columbia is from March to June, with smaller numbers moving throughout the year (McConnell and Snyder, ms 12). Water temperature during this period is within the optimum range for migration.

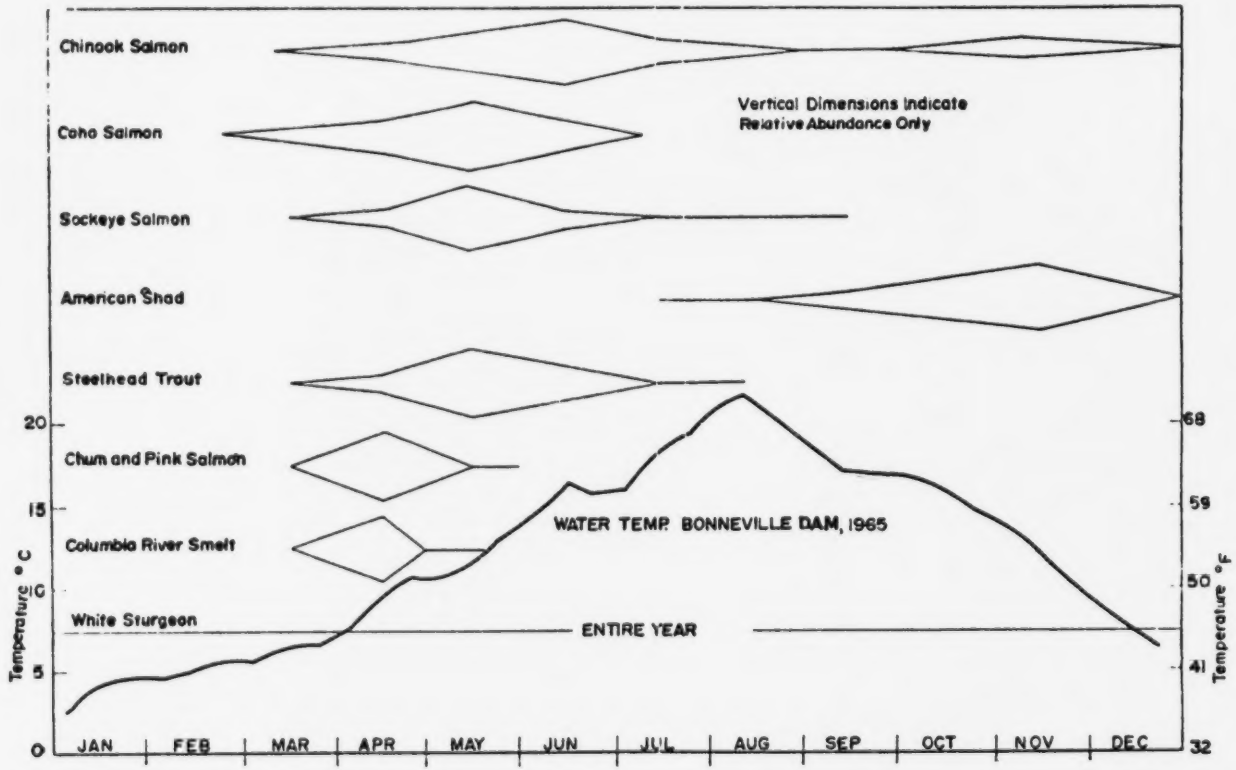

Figure 7. Relative abundance of young anadromous fishes and sturgeon in the lower Columbia River, in relation to season and water temperatures. (Coutant and Becker, 1968)

Distribution of Juvenile Migrants in Stream Cross-Section

The distribution of seaward migrant chinook salmon in the stream cross-section was studied by Mains and Smith (1964) near the confluence of the Columbia and Snake Rivers. The horizontal distribution was similar on both rivers, with some preference for the shore at both locations. Vertical distribution favored the surface on the Columbia, but there was more general distribution in the Snake River.

From several years of sampling in the Columbia River estuary, the National Marine Fisheries Service has generally established the migration patterns of juvenile salmon migrants from the mouth of the river to Bonneville Dam. Although each species is different, generally the smaller fish which migrate in their first year (fall chinook, chum) are found in shallow water near the beaches. The yearling migrants (spring chinook, coho, sockeye, and steelhead) are most abundant in deeper water and more evenly distributed or, in the case of sockeye, concentrated in mid-channel. A proportion of the fall chinook has been found to hold for varying but extended periods of time throughout the year in the vicinity of Puget Island (RM 44).

The cross-section studies generally indicate that smaller downstream migrants move closer to shore, while some larger fish and selected species are found more evenly distributed or in mid-channel.

Passage of Juvenile Migrants Through Thermal Plume

When the current studies were being planned, the question perhaps uppermost in the minds of fishery biologists considering thermal effects was the fate of downstream migrating salmonids who might pass through a thermal plume created by a thermal power plant discharge. Since the Hanford Atomic Works had been discharging heated effluents to the Columbia for many years and the AEC had contracted for studies of the biological effects of the discharges, attention centered upon those studies. Few others had seen the plumes and none had access to the classified information concerning the temperature of the effluent or its mixing characteristics. The AEC researchers subsequently submitted papers for publication describing studies designed to answer some of these questions (Becker and Coutant, ms 36; Becker, Coutant and Prentice, ms 37).

Theoretically, an unknown portion of the downstream migrating salmonids would pass through the mixing zones below the heated discharges. To test the effects of this theoretical occurrence, a floating trap was "fished" in the effluent plume (K reactor) for four days in May 1968. Water temperatures in the trap ranged from 52.7 to 59.9 F (11.5 to 15.5 C) during this period. The catch consisted of 174 small chinook; eight mortalities occurred in this group which were attributed to mechanical injury. In a similar effort in October and November of the same year, no fish were trapped.

Additional tests of thermal effects in 1968 and 1969 involved drifting of caged juvenile salmon through the center of a plume. Most drifts resulted in no loss of fish; however, one drift through

the main K-reactor plume in mid-river resulted in total mortality. Most drifts through the K-reactor plume resulted in low thermal "doses" because the exposure duration was too short to cause excessive mortality even though 77 F (25 C) was exceeded. The researchers concluded from the two years of study that, under certain environmental conditions (low river flow-high river temperature), the potential clearly exists for lethal exposure to migrating juvenile fish.

The proportion of the juvenile salmonid migrants which would enter the mixing zone in the mid-stream plume is not known. However, it is considered to be small due to the disproportionately low ratio of effluent volume to total water mass. The velocity of river flow through the plume is 0.16 to 3.3 feet per second (0.5 to 1 meters per second), and the lethal temperatures within the plume exist for only a relatively short distance in the mixing turbulence before dispersal to sublethal levels even at low flows. Approximately 80 percent of the difference between plume temperature and background river temperature is lost within five seconds of discharge as measured at the surface (Becker, Coutant, and Prentice, ms 37).

The area of perhaps greater potential danger is the inshore K-reactor shoreline leakage area where total mortalities occurred on two drifts of salmon through the area. The lower velocities and reduced mixing rate make this area and any similar situations of potentially greater concern.

General conclusions regarding the effects of thermal plumes in the Hanford area upon downstream juvenile migrants, are that the number of fish affected is probably small, as is the risk of a

directly lethal dose, due to the velocity of the stream and rapid mixing. The sublethal, or indirectly lethal, effects of plume exposure are discussed under predation and gas bubble disease.

Thermal Resistance of Migrating Juveniles

As in the case of adults, the thermal resistance of juvenile salmonids to temperatures outside their tolerance range, or to drastic changes in temperature within their tolerance range, is a factor of both the degree of temperature difference and the length of exposure. In fact, thermal dose (time and temperature) is more significant in the case of juveniles since their smaller mass allows the fish tissues to heat up quicker. The preferred temperature range for juvenile salmonids is 41 to 62.6 F (5 to 17 C) (Brett, et al., 1969; Averett, 1969).

The maximum swimming performance of juvenile coho salmon after exposure to abrupt thermal changes was tested by Groves (ms 14); temperature changes were within the range from 41.4 to 73 F (5 to 23 C). He concluded that, if temperature alone is considered, a thermal change does not reduce the ability of the fish to make maximal swimming efforts. "Migrant juvenile coho salmon probably could routinely experience sudden prolonged thermal changes spaced anywhere within their acceptable thermal range and still be able to make the maximal swimming efforts demanded by such life emergencies as rapid evasion and defense."

In studies to further define the lethal effects of thermal shock, four species of juvenile salmon plus steelhead were used in thermal

shock studies by the NMFS (Snyder and Blahm, ms 8). Fish were exposed to shock temperatures of 78.8 and 84.2 F (26 and 29 C) from acclimation temperatures ranging from 39.2 to 68 F (4 to 20 C). One hundred percent mortality occurred in less than three hours at 78.8 (26 C) and in twenty-five minutes at 84.2 F (29 C). Fifty percent mortality was recorded in less than two hours at 78.8 F (26 C) and within eight minutes at 84.2 F (29 C). The death process was found to be reversible at 78.8 F (26 C) but not at 84.2 F (29 C) if the fish were returned to the control water temperature as soon as loss of equilibrium was noticed.

A program of research on thermal resistance using Columbia River water for experimentation has been conducted by the National Marine Fisheries Service. Water pumped from the river was thermally adjusted to simulate temperature conditions (Snyder, Blahm, and McConnell, ms 29). All fish were acclimated in the river water at the experimental facility prior to the test. Acclimation temperatures in the tests ranged between 50 and 68 F (10 and 20 C). In some cases, little or no mortality occurred at a temperature below 73.4 F (23 C), while in a few cases significant mortality occurred at temperatures as low as 62.6 F (17 C). The investigators concluded that:

1. Water quality other than temperature played a critical role in these tolerance tests.

2. High nitrogen (N_2) gas saturation probably produced the most important indirect effect with imposed temperature increases.

3. Resistance levels were reduced in most cases 5.4 to 9 deg. F (3 to 5 deg. C) from perviously published laboratory findings and time to death was shortened.

4. Mortalities occurred at test temperatures which were similar to naturally occurring river water temperatures.

The ultimate upper lethal temperature for juvenile salmon is apparently between 73.4 and 77 F (23 and 25 C) if other stresses are minimal. (Refer to Chapter III and Figure 5.) However, in the presence of additional stresses (e.g., sublethal nitrogen supersaturation), a temperature of 68 F (20 C) or lower may be lethal within one week. Temperature in excess of 68 F (20 C) ". . . may be considered suboptimum for survival of juvenile salmonids in river ecosystems" (Becker, Coutant, and Prentice, ms 37).

In order to summarize the results of the many studies of thermal resistance of juvenile salmonids, the pooled data was used to construct the minimum mean thermal resistance curves in Figure 8. Data are included from Brett (1952), Coutant and Dean (ms 33), Mighell (ms 17), Blahm and McConnell (ms 3), Blahm and Parente (ms 4), Snyder and Blahm (ms 5), Snyder and Craddock (ms 6), Blahm and McConnell (ms 7), and Snyder and Blahm (ms 8) from tests on chinook, sockeye, coho, and steelhead. Mean survival time (in minutes) is scaled on the ordinate with temperature on the abscissa.

In thermal resistance tests it is standard procedure to measure the median resistance time (time to 50% mortality) of test animals exposed to a given temperature. Survival time increases at an exponential rate at progressively decreasing test temperatures. Connecting most of the points on a graph of the logarithm of time plotted against temperature produces a straight, sloping line (Figure 8). A point

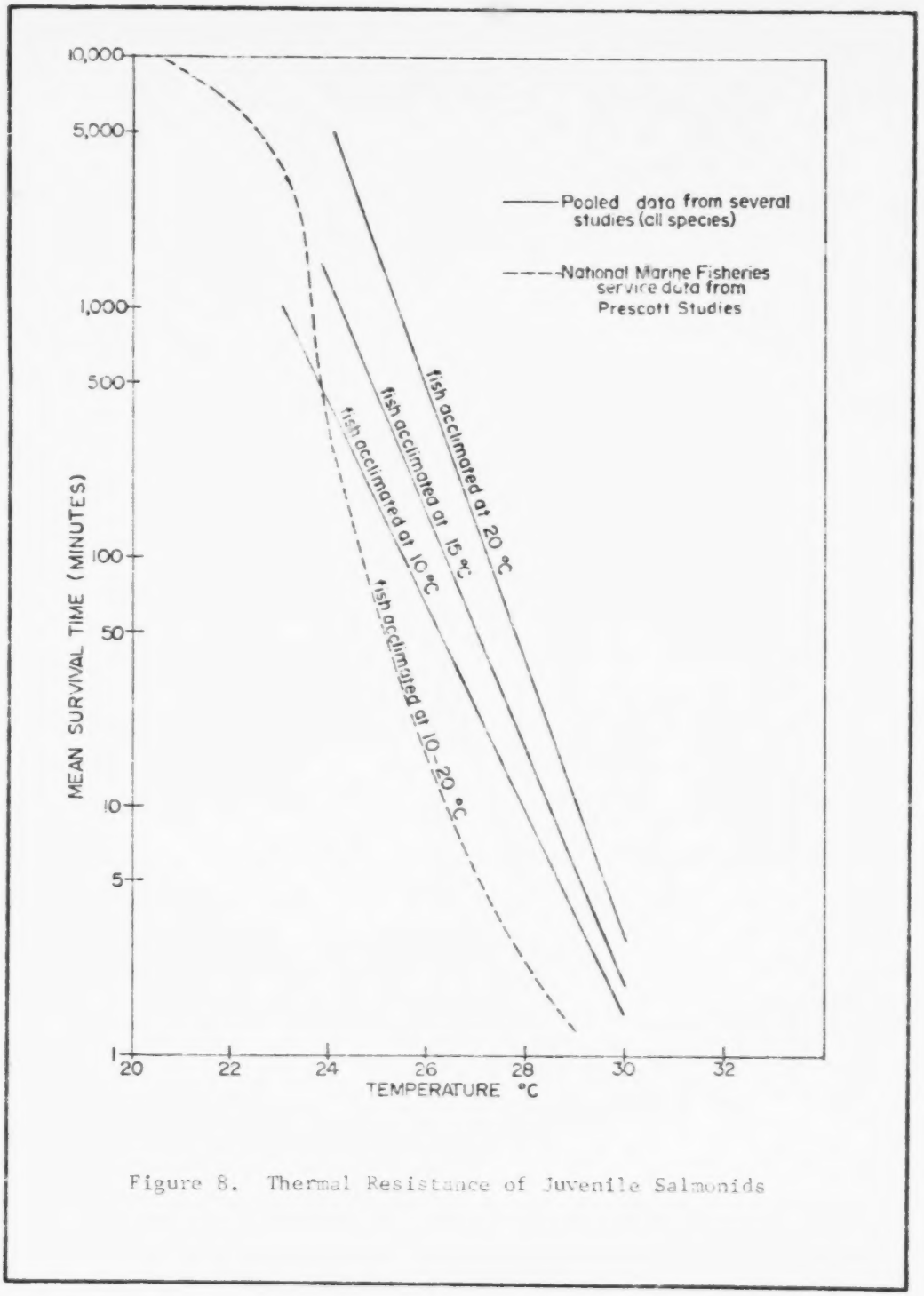

Figure 8. Thermal Resistance of Juvenile Salmonids

is reached at the upper end of a line (for a given acclimation temperature of test animals) at which 50% mortality will never occur regardless of time of exposure. This is termed the "incipient lethal temperature."

Figure 8 was constructed by plotting the results on semi-log graph paper of all comparable studies for a given acclimation temperature and drawing a line (by inspection) through most of the points. While this method gives an approximation, the error is not significant from a practical standpoint and permits simplification of a complex subject. Some results, particularly those of the National Marine Fisheries Service at the Prescott Laboratory, were noticeably different from the others and are shown by the dashed line. Reasons for these differences are discussed on page 60.

For every degree of temperature increase it is noted that the survival time is decreased from 50 to 75 percent regardless of the acclimation temperature. It is also apparent that as the temperature increases the difference in acclimation temperatures is less significant (the resistance lines become closer together).

To test the element of time of exposure to juvenile thermal resistance, fall chinook fry which were acclimated to 48.2 F (9 C) were abruptly exposed to 86 F (30 C) waters over intervals ranging from 5 to 35 seconds (Groves and Mighell, ms 15). The fish were affected in direct proportion to the duration of exposure. At 5 seconds exposure, no loss of equilibrium or mortality was observed. At a 10 second exposure, equilibrium loss occurred in 16 percent of the fish and increased at a linear rate up to where 100 percent showed equilibrium losses at 35 seconds exposure.

Yearling sockeye, coho and steelhead were tested to determine the effects of their previous temperature acclimation upon their resistance to high lethal temperature (Mighell, ms 17). Fish acclimated at 41, 50, 59, 68, and 73.4 F (5, 10, 15, 20, and 23 C) were tested at exposure to 82.4, 86, and 89.6 F (28, 30 and 32 C). Results showed that, at all test temperatures, the trend was for increased resistance to loss of equilibrium and death as acclimation temperatures increased. The author notes the mean survival time in relation to previous acclimation temperature increased markedly at 82.4 F (28 C), particularly for coho and steelhead, and suggests that this may be a critical upper limit in order for acclimation to significantly influence resistance to heat. Resistance was greatest in steelhead, followed by coho and sockeye. Size of the fish within the ranges tested did not affect resistance times to death or loss of equilibrium.

Using a test flume and actual passage through a condenser tube, Kerr (1953) tested thermal resistance of juvenile chinook salmon at the Contra Costa stream plant on the Sacramento River. In flume tests, fish ranging from 1.34 to 2.4 inches long were exposed for ten minutes without acclimation to temperature rises in increments from 0 deg to 27 deg F (0 - 15 deg. C) and from a minimum water temperature of 55-56 F (12.8-13.3 C) to a maximum water temperature of 83 F (28.3 C). "It was found from these experiments that small yearling salmon could withstand an instantaneous temperature rise of 25 deg. F (13.9 deg. C) without loss of life and that their maximum temperature

tolerance was approximately 83 F (28.3 C)" (Kerr, op. cit.). In condenser tests, fish were exposed to 16 deg. F (8.8 deg. C) temperature rises for 3.5 to 5 minutes with no mortalities. No mortalities occurred in flume-tested fish held for 24 hours; a three percent mortality occurred to condenser-tested fish held for ten days. (The fish in these experiments did not receive a lethal dose).

Generalized conclusions regarding the thermal resistance of juvenile salmonids indicate that the effects of a rapid temperature increase is directly proportional to duration of exposure. Acclimation to higher temperatures significantly increases temperature resistance. Differences between species are small, and all investigators using fish that were not prestressed achieved essentially the same results. Fish stressed by nitrogen supersaturation, toxicants, or disease have reduced temperature resistance; therefore, temperatures should desirably be maintained well below the upper lethal limits to insure ultimate survival. Brett (1960) recommended that the upper temperature limit "required" for any species be 5.4 deg F (3 deg C) below the ultimate upper lethal temperature to avoid significant curtailment of activity. Temperatures above 68 F (20 C) are considered to be adverse for juvenile salmonids, while temperatures near 62.6 F (17 C) may be considered to be a maximum optimum temperature. Between 62.6 and 68 F (17 and 20 C), any increase in temperature is of no benefit to juvenile salmonids while increasing requirements for food, the possible synergistic action with toxic materials, and the liklihood of disease infection.

Predation

Increased susceptibility to predation of juvenile salmonids has been assumed to occur when the fish have been subjected to the debilitation or shock of adverse water temperatures. Several studies to define the relationship between temperature and predation have been conducted.

Coutant (ms 31) speculated that, since loss of equilibrium was an obvious behavioral response to a sublethal dose of a lethal temperature, then smaller doses would also have a behavioral effect. A series of laboratory experiments were designed to test the differential predation rates at varying temperature levels. The tests sought to determine if non-detectable behavioral changes would be reflected in predator success when compared with untreated control fish. Thermally shocked juvenile rainbow trout and chinook salmon were selectively preyed upon by larger fish when shocked and unshocked fish were subjected simultaneously to the predators (large rainbow trout). Statistically significant increases in predation rates occurred at thermal doses which were a fraction of the dose which causes visible equilibrium loss--ten percent in the case of chinook and 20 percent in the case of rainbow.

Further experiments were conducted to determine if the predator response paralleled thermal dose responses of visible equilibrium loss and death (Coutant, ms 32); that is, is predation response a function of temperature and exposure time? Rainbow trout fingerlings acclimated to 59 F (15 C) were subjected to three levels of lethal temperature for various lengths of time. The fish were removed from

the shock temperatures at intervals and immediately exposed to the large predator rainbow trout along with control fish. A statistically significant difference in predation on the two groups was evident in 0.55 minutes at 30 C, at two minutes at 28 C, and 32 minutes at 20 C. The treated fish were more readily captured by the predators.

Similar results were found by Sylvester (ms 18) using coho for predators and underyearling sockeye for prey, although no control groups were used. In a series of experiments at acclimation temperatures of 44.5, 53.6, and 62.6 F (7, 12, and 17 C) he found that a thermal dose of 18 deg. F (10 deg. C) for sixty seconds significantly increases a prey's susceptibility to predation. The results were similar for five second exposure to incremental temperatures ranging from 23.4 to 41.4 deg. F (13 to 23 deg. C).

It should be remembered that the prey fish in these laboratory experiments had no opportunity for excape as would be available in natural conditions. However, the general conclusion that predators select fish whose behavior has been altered by temperature stress appears well substantiated.

Infectious Diseases

Infectious diseases of juvenile salmonids have been extensively studied in connection with hatchery operations, but less work has been done relating disease incidence with higher temperature than has been done with adults.

Studies with hatchery-reared juvenile rainbow trout showed that a number of factors are involved in the relationship between temperature

and columnaris, including immunity, species, age, condition, other disease, crowding and difference in columnaris strain virulence (Fujihara, Olson, and Nakatani, ms 44). They pointed out that the highest mortalities occurred during the initial temperature rise and not during the peak temperatures of the summer.

Recent studies on the relationship between water temperature and mortalities of rainbow trout caused by Ceratomyxa shasta, a myxosporidian, have been conducted at Oregon State University. Little evidence was found for a trend between temperature and total percent infectivity due to C. shasta. A strong relationship, however, was found between temperature and survival time of the host. One hundred percent mortality of exposed fish occurred in 17 days at 69 F (20.6 C) and 95 percent mortality in 56 days at 54 F (12.2 C) (Udey and Fryer, unpublished). The full significance of these findings cannot be appreciated without further study.

Gas Bubble Disease

Gas bubble disease is considered to be one of the most significant water quality problems causing mortalities of downstream migrating salmonids in the Columbia River. (For a description on the disease and the nitrogen conditions in the Columbia River, see the chapter on adults.) Although much of the evidence is as yet circumstantial, the physical extent of the problem has been defined by Ebel (1970 C). Of the downstream migrants arriving at Ice Harbor Dam on the Snake River, 25-45 percent of the chinook and 30-58 percent of

the steelhead fingerlings exhibited visible gas bubble disease symptoms. These observations support those of Raymond (1970) that 70 percent of the population of downstream migrant chinook from the Salmon River was lost between Whitebird and Ice Harbor Dam. An estimate for steelhead produced from Dworshak hatchery indicated a 25-30 percent loss to Ice Harbor Dam and about a 70 percent loss to McNary Dam. Dissolved nitrogen supersaturation levels during the period of downstream migration reached a peak of 146 percent saturation in the forebay of Lower Monumental Dam in 1970.

Preliminary studies have been reported by Coutant (ms 34) in which he explores the possible effects of nitrogen supersaturation upon juvenile salmonids passing through the Hanford thermal plumes. He attempted to define the levels of gas supersaturation and temperature change required to produce identifiable synergistic effects resulting in mortality of juvenile salmonids. His results show that fish prestressed with high nitrogen saturation levels (115 percent) suffered higher mortalities from a thermal shock than did fish subjected to the thermal shock at normal saturation values. However, since the rate of passage through the plume is relatively rapid (0.5-1.0 meters per second), he concludes that the juvenile migrants would be exposed to temperature increases greater than 5.4 deg. F (3 deg. C) for only a few minutes, resulting in sublethal doses. Coutant concludes from his lab studies that fish passing through the Hanford plumes would not experience stresses from temperature-induced supersaturation sufficient to cause significant mortalitites, either immediate or thirty days after the experience.

Studies conducted by Ebel et al. (ms 13) verify the detrimental effects of nitrogen supersaturation and temperature conditions. The data indicate:

1. Supersaturation of nitrogen drastically affects the tolerance of juvenile coho, chinook and steelhead to temperature increases.

2. Acclimation to higher temperatures is of some value to the fish in withstanding nitrogen supersaturation. However, the 50 percent mortality level will be reached in less than 18 hours at all acclimation temperatures when nitrogen supersaturation levels are 125-130 percent.

3. When supersaturation of nitrogen is present, depth is an important compensating factor when fish are able to "sound".

4. During periods of nitrogen supersaturation, any increase in temperature will be detrimental to migrating juvenile salmonids.

The concern of the fisheries biologists is substantiated that supersaturation of nitrogen is a significantly detrimental factor weighing against successful downstream migration of juveniles and that the effects of supersaturation are accentuated by temperature increases. At saturation levels over 115 percent, any increase in temperature could be damaging due to temperature-gas solubility relationships.

Toxicity

The relationship of temperature to metal toxicity was shown by Bouck et al. (ms 1) in laboratory bioassay studies. Juvenile steelhead and rainbow trout were exposed to toxicant concentrations

ranging from existing (control) levels in Willamette and Columbia River waters to 100 percent concentration of the allowable levels of ten toxicants. Results show the 96 hour TL_m (tolerance limit median) concentrations were inversly related to increasing temperatures. As the test temperature rose from 5 C to 20 C the 96 hour TL_m dropped to about half the former value.

Beneficial Effects

The beneficial effects of rearing catfish, shrimp, and oysters in thermal effluents have been demonstrated in several small scale experiments but only two references to rearing salmonids in heated water are reported (Matthiason, in press; Wallis, in press). Carton and Chriastianson, (in press) and Coutant (in press) pointed out some problems to the use of waste heat for aquaculture including demonstration of economic feasibility, design of a system to maintain proper temperatures, and public acceptance of a product cultured in an environment containing traces of radioactivity.

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VI - THERMAL EFFECTS ON NON-SALMONID FISH

While salmonid fish were the prime target of the biological effects studies and review as a part of the Columbia River Thermal Effects Study, other species of cold-water fish are found in the Columbia River which would be pertinent to the over-riding concern for water quality standards to protect and enhance aquatic life. The following discussion presents a brief summary of the limited information available on the temperature requirements and tolerances of these non-salmonid fish.

The National Marine Fisheries Service, in studies of the occurrence of fish in the vicinity of its research barge on the Columbia River (RM 68), found twenty-seven species of fish (McConnell and Snyder, ms 12). Twenty-one of these species were non-salmonid and accounted for 43 percent of their total catch. The non-salmonid species which were captured throughout the year included three-spine stickleback, Columbia River chub, and starry flounder. The non-salmonid fish of commercial and sport value were American shad, white sturgeon, and eulachon (smelt).

In temperature studies on the eulachon, Smith and Saalfeld (1955) reported the fish entered the Columbia River when the temperature was between 33.8 and 50 F (2 and 10 C) but they migrate up to and beyond the Cowlitz River (RM 68) when the Columbia is approximately 40 F (4.4 C). The smelt run was delayed five weeks from entering the Cowlitz River because of low water temperatures during December 1968

and January 1969 (Snyder, ms 27). Eulachon eggs appear to be more tolerant than adults to temperature increases. The eggs can withstand a temperature of 25.2 F (14 C) from a base temperature of 39.2 to 46.4 F (4 to 8 C) without appreciable mortalities (Parente and Ambrogetti, ms 26), but a 5.4 deg. F (3 deg. C) increase halts maturation of adult females. In tests in 1968 and again in 1969, it was observed that female smelt exposed to water heated 7 deg. F (3.89 deg. C) above river temperatures were reluctant to spawn. The studies on smelt indicate that those fish have a lower lethal temperature limit than do the salmonids and a lower optimum temperature preferendum. Adult female smelt are less tolerant of temperature changes than other fish.

Thermal tolerance tests on yellow perch showed a 50 percent mortality level at 89.6 F (32 C) in 2.4 hours (Blahm and Parente, ms 10). A chill period at about 42.8 F (6 C) for an undefined period of time is important to induce reproductive development and spawning in yellow perch.[8/] Thermal tolerance studies on three spine stickleback indicate a 50 percent mortality level at 78.8 F (26 C) in about 6 days (Blahm and Parente, ms 10). Thus, both yellow perch and three-spine stickleback have a higher thermal tolerance than do the salmonids.

8/ Mr. Bernard Jones at the National Water Quality Laboratory, Duluth, Minnesota.

VII - SECONDARY PRODUCTION ORGANISMS

Limited studies in other areas of the world have shown the potential for adverse effects of a large thermal discharge upon elements of the food chain. In terms of the ecology of the river system, disruption of the food chain through destruction of the smaller organisms could have serious consequences to the fish resources of the Columbia River. Little information is available on the secondary food organisms in the Columbia River or the thermal effects on those organisms.

Specific Foods

Among some fishery biologists, there has been a popular conception that certain particular foods are required by juvenile salmonids at various stages of their development (Davidson, 1965). Zooplankton (*Daphnia pulex*) was found to be the dominant food organism of juvenile coho in Lake Merwin, while insects were the dominant food in Speelyai Creek, a tributary (Hamilton et al., 1970). Insects formed a major portion of the diet of juvenile chinook migrating through the lower Columbia River in spring and fall months, whereas zooplankton were of major importance from July through October (Craddock and Parente, ms 24). Fish were highly selective on the larger plankton (*Daphnia*). Availability of insects was not studied so it was not known if this was a matter of preference or availability.

Becker (ms 40) found that larval and adult forms of aquatic insects (Tendipedidae) were the primary food of even the smallest chinook fry in the Hanford reach of the Columbia River. His opinion, and that of most investigators, is that salmon are opportunistic feeders and take whatever food is most readily available to them. There is reason to believe this holds true throughout their life.

Food requirements are more specific for some non-salmonid fish residing in the Columbia River estuary (Haertel and Osterberg, 1967).

Plankton

Plankton populations in the Columbia River vicinity of Prescott, Oregon, were studied by Craddock and Parente (ms 24) in 1968 and 1969. Daphnia and Bosmina were found to be the dominant genera of cladocerans, the most abundant plankton organism. Daphnia was most abundant at the surface and its peak of abundance occurred simultaneously with maximum water temperature in August. Bosmina was uniformly distributed from 5 to 15 meter (16.4 to 49.2 foot) depths and peak abundance was in June or July, with a second peak in October and November.

Thermal Effects on Secondary Organisms

From observations of the thermal effects in the Hanford reach of the Columbia River, Coutant (1968) indicates caddis flies emerge about two weeks earlier at a point 14 kilometers below the lowermost Hanford thermal discharge when compared to caddis flies at a point 16 kilometers above the discharges. Temperatures at the two points were 54.5 and 52.3 F respectively (12.5 and 11.3 C).

Thermal shock studies were conducted on the plankton Daphnia by Craddock (ms 23). He found that a fifteen minute exposure to 86 F (30 C) seemed to have little effect on survival of the plankton, which had been previously acclimated to 59 F (15 C). Continued exposure caused a fifty percent mortality in about twenty-four hours, and a hundred percent mortality in about forty-eight hours.

Studies on the opposum shrimp, an important plankton of the Sacramento River, by Hair (1971) showed that it can stand a rapid temperature rise of 25 deg. F (13.9 deg. C), provided the exposure time is short and that the ultimate temperature does not reach a critical maximum of 87 F (30 C).

From the limited information available, then, it can be generally concluded that the planktonic organisms are more resistant to thermal shock than are the fish species that feed upon them.

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APPENDIX A

MANUSCRIPTS

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	FEDERAL WATER QUALITY ADMINISTRATION
1	Bouck, G., G. Chapman, P. Schneider, D. Stevens, and J. Jacobson, "Initial Studies of Temperature Requirements of Adults Sockeye Salmon (Oncorhynchus nerka), Adult Coho Salmon (Onocorhynchus kisutch), and Thermal-Chemical Requirements of Juvenile Steelhead Trout (Salmo gairdneri) in the Columbia River", October 1970.
	NATIONAL MARINE FISHERIES SERVICE
	Adult Salmon Behavior in River
2	Monan, Gerald E., Kenneth L. Liscom, and Jim R. Smith, "Sonic Tracking of Adult Steelhead in Ice Harbor Reservoir, 1969", July 1970.
	Thermal Tolerance of Juvenile Salmonids
3	Blahm, Ted H., Robert J. McConnell, "Effect of Increase Water Temperatures on the Survival of Spring and Fall Juvenile Chinook Salmon (Oncorhynchus tschawytscha) from the Lower Columbia River", August 1970.
4	Blahm, Ted H. and William D. Parente, "Survival of Juvenile Chum Salmon Exposed to Elevated Temperatures in Columbia River Water", July 1970.
5	Snyder, George R. and Ted H. Blahm, "Mortality of Juvenile Chinook Salmon Subject to Elevated Water Temperatures", August 1970.
6	Snyder George and Donovan R. Craddock, "Effect of Temperature Increases on Juvenile Steelhead Trout (Salmo gairdneri) from the Columbia River", August 1970.

Manuscript Number	
	Thermal Shock of Juvenile Salmonids
7	Blahm, Ted H. and Robert J. McConnell, "Survival of Juvenile Coho Salmon Exposed to Sudden Water Temperature Increases", August 1970.
8	Snyder, George R. and Ted H. Blahm, "Survival Times of Juvenile Salmonids Exposed to Water Temperatures Causing Thermal 'Shock'", August 1970.
	Thermal Tolerance of Non-Salmonids
9	Blahm, Ted H. and Robert J. McConnell "Mortality of Adult Eulachon (Thaleichthys pacificus) Subjected to Sudden Increases in Water Temperature", July 1970.
10	Blahm, Ted H. and William D. Parente, "The Effect of Increased Water Temperatures on the Survival of Adult Threespine Stickleback (Gasterosteus aculeatus) and Juvenile Yellow Perch (Perca flavescens) in the Columbia River", August 1970.
11	Blahm, Ted H. and William Parente, "A Record of the Development of the Shad Egg (Alosa sapidissima)", August, 1970.
	"On Site" Timing of Movement of Juvenile Fish at Prescott, Oregon
12	McConnell, Robert J. and George R. Snyder, "Occurrence of Fish in the Vicinity of Proposed Sites of Two Nuclear Electric Plants on the Lower Columbia River", August 1970.
	Effect of Supersaturation of Nitrogen on Juvenile Salmonids in the Columbia River
13	Ebel, Wesley J., Earl M. Dawley, and Bruce Monk, "Thermal Tolerance of Juvenile Salmon in Relation to Nitrogen Supersaturation", September 1970.

Manuscript Number	
	Effects of Temperature Acclimation on Resistance to Thermal Challenge
14	Groves, Alan B., "Maximal Swimming Performance of Juvenile Coho Salmon (Oncorhynchus kisutch) Following Abrupt Thermal Change", August 1970.
15	Groves, Alan B. and James L. Mighell, "Thermal Dose and Equilibrium Loss in Chinook Salmon Fry (Oncorhynchus tschawytscha) (Summary)", August 1970.
16	McConnell, Robert J. and Ted H. Blahm, "Resistance of Juvenile Sockeye Salmon (Oncorhynchus nerka) to Elevated Water Temperatures", September 1970.
17	Mighell, James L., "Effects of Acclimation on Resistance of Juvenile Salmonids to High Lethal Temperatures", September 1970.
18	Sylvester, J. R., "Thermal Dose and Predator Avoidance in Sockeye Salmon", July 1970.
	Limnological Survey of Lower Columbia River
19	Clark, Shirley M. and George R. Snyder, "Limnological Study of Lower Columbia River, 1967-68", February 1970.
20	Clark, Shirley M. and George R. Snyder, "Timing and Extent of a Flow Reversal in the Lower Columbia River", November 1969.
21	Snyder, George R. and Robert J. McConnell, "Frequency and Duration of the Reversal of Direction of River Flow in the Lower Columbia River, April 1968 - March 1970", August 1970.
22	Snyder, George R. and Robert J. McConnell, "Subsurface Water Temperatures of the Columbia River at Prescott, Oregon (River Mile 72), 1968-69", April 1970.

Manuscript Number

Thermal Tolerance of Zooplankton of Lower Columbia River

23 Craddock, Donovan R., "Thermal Effects on an Important Zooplankter (Daphnia pulex) of the Columbia River", July 1970.

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25 Anonymous, "The Effect of Water Temperature Increase on Spawning of Columbia River Smelt", (Working Paper), May 1969.

26 Parente, William D. and Walter J. Ambrogetti, "Survival of Eulachon Eggs (Thaleichthys pacificus) at Different Water Temperatures", August 1970.

27 Snyder, George R., "Thermal Pollution and the Columbia River Smelt", July 1970.

Prediction of Environmental Conditions in John Day Reservoir

28 Novotny, Anthony J. and Shirley Miller Clark, "Preliminary Predictions of Water Temperatures in John Day Reservoir".

General

29 Snyder, George R., Theodore H. Blahm, and Robert J. McConnell, "Floating Laboratory for Study of Aquatic Organisms in their Environment".

30 Snyder, George R., Donovan R. Craddock, and Ted H. Blahm, "Thermal Effects Studies on the Lower Columbia River, 1968-70", August 1970.

Manuscript Number

ATOMIC ENERGY COMMISSION

Performance of Thermally Shocked Young Salmon

31 Coutant, C. C., "Relative Vulnerability of Thermally Shocked Juvenile Salmonids to Predation", January 15, 1970.

32 Coutant, C. C., "Relative Vulnerability of Thermally Shocked Juvenile Salmonids to Predation. II. A Dose Response in Rainbow Trout", February 4, 1970.

33 Coutant, Charles C. and John Mark Dean, "Relationships Between Equilibrium Loss and Death as Responses of Juvenile Chinook Salmon and Rainbow Trout to Acute Thermal Shock".

Gas Bubble Disease of Young Salmonids

34 Coutant, Charles C., "Exploratory Studies of the Interactions of Gas Supersaturation and Temperature on Mortality of Juvenile Salmonids, September 28, 1970.

Sonic Tracking of Adult Salmonids

35 Coutant, C. C., "Behavior of Sonic Tagged Chinook Salmon and Steelhead Trout Migrating Past Hanford Thermal Discharges (1967)",

Effect of Thermal Shock from Effluent Discharges on Young Salmon

36 Becker, C. D., C. C. Coutant, "Experimental Drifts of Juvenile Chinook Salmon through Effluent Discharges at Hanford in 1968", September, 1970.

37 Becker, C. D., C. C. Coutant, and E. F. Prentice, "Experimental Drifts of Juvenile Salmonids through Effluent Discharges at Hanford, Part II. 1969 Drifts and Conclusions", July 15, 1970.

Manuscript Number	Temperature Tolerances of Adult Salmon
38	Coutant, Charles C., "Thermal Resistance of Adult Coho (Oncorhynchus kisutch) and Jack Chinook (O. tschawytscha) Salmon, and Adult Steelhead Trout (Salmo gairdneri) from The Columbia River", October 1970.
	Hanford Chinook Salmon Population Studies
39	Watson, D. G., "Fall Chinook Salmon Spawning in the Columbia River near Hanford 1947-1969", October 1970.
	Relationship of Thermal Discharge to Food and Feeding of Juvenile Chinook Salmon
40	Becker, C. D., "Food and Feeding of Juvenile Chinook Salmon in the Central Columbia River in Relation to Thermal Discharges and Other Environmental Features', August 1, 1970.
41	Becker, C. D., "Temperature, Timing and Seaward Migration of Juvenile Chinook Salmon from the Central Columbia River", July 1970.
	Effects of Temperature on C. Columnaris, Dermocystidium Salmonis, and A. Salmonicida Fish Disease
42	Fujihara, M. P. and F. P. Hungate, "Seasonal Distribution of Chondrococcus columnaris Disease in River Fishes: A Procedure Using Antibody Synthesis in Fishes as a Survey Technique", October 1, 1970.
43	Fujihara, M. P. and R. E. Nakatani, "Antibody Production and Immune Response of Rainbow Trout and Coho Salmon to Chondrococcus columnaris", October 1, 1970.
44	Fujihara, M. P., P. A. Olson, and R. E. Nakatani, "Chondrococcus columnaris Disease of Fishes: Influence of Water Temperature, Age and Size on Susceptibility", June 15, 1970.

Manuscript Number	
	Effects of Fluctuating Temperatures on Survival and Growth of Juvenile Chinook Salmon
45	Olson, P. A. and R. E. Nakatani, "Effects of Chronic Variable Water Temperatures on Survival and Growth of Young Chinook Salmon".
46	Olson, P. A., R. E. Nakatani and T. Meekin, "Effects of Thermal Increments on Eggs and Young of Columbia River Fall Chinooks".
47	Olson, P. A. and W. L. Templeton, "Effects of Fluctuating Temperatures on Fall Chinook Eggs and Young".
48	Olson, P. A. and W. L. Templeton, "Effects of Temperature Increments on Juvenile Steelhead".
	Thermal Effects on Secondary Production Organisms
49	Coutant, Charles C., "Thermal Pollution - Biological Effects a Review of the Literature of 1969", February 15, 1970.
50	Coutant, Charles C., "Thermal Pollution - Biological Effects a Review of the Literature of 1968", February 17, 1969.
51	Coutant, C. C. and C. D. Becker, "Growth of Columbia River Limpets, Fisherola Nuttalli (Haldeman), in Normal and Reactor-Warmed Water", August 15, 1970.

APPENDIX B

MEMBERSHIP OF THE TECHNICAL ADVISORY COMMITTEE FOR BIOLOGICAL EFFECTS
Columbia River Thermal Effects Study

State Representatives

H. J. Rayner, Ph. D.	Oregon State Game Commission
James B. Haas	Fish Commission of Oregon
Glen D. Carter	Oregon Department of Environmental Quality
Emanuel H. LeMier	Washington Department of Fisheries
Jack Ayerst	Washington Department of Game
Roland E. Pine	Washington Department of Ecology
Monte Richards	Idaho Department of Fish and Game
Robert P. Olson	Idaho Department of Health
Ralph W. Boland	Montana Department of Fish and Game

Federal Representatives

L. Edward Perry, Ph. D.	Bureau of Sport Fisheries and Wildlife, Department of the Interior
Vernon C. Bushnell, Ph. D.	Bureau of Reclamation, Department of the Interior
Fred Limpert	Bonneville Power Administration, Department of the Interior
Edward M. Mains	Corps of Engineers, Department of the Army

Power Organization Representatives

George Eicher	Portland General Electric Company
Roy Hamilton, Ph. D.	Pacific Power and Light Company
Sam Billingsley	Washington Public Power Supply System

APPENDIX C

State Water Temperature Standards

The water temperature standards adopted for the Columbia River by the States of Oregon and Washington are as follows:

Oregon	Washington
No waste discharge or activity will cause any measureable increase when river temperatures are 68 F. or above, or more than 2 F. increase when river temperatures are 66 F. or less.	No measurable increase shall be permitted within the waters designated which result in water temperatures exceeding 68 F. nor shall the cumulative total of all such increases arising from unnatural causes be permitted in excess of t=110/ (T-15); for purposes here, "t" represents the permissive increase and "T" represents the resulting water temperature.

APPENDIX D

Scientific Names of Fish and Other Aquatic Organisms

Salmon	
chinook	*Oncorhynchus tschawytscha*
coho	*Oncorhynchus kisutch*
sockeye	*Oncorhynchus nerka*
pink	*Oncorhynchus gorbuscha*
chum	*Oncorhynchus keta*
Trout	
steelhead	*Salmo gairdneri*
speckled	*Salvelinus fontinalis*
Atlantic salmon	*Salmo salar*
Other Species	
smelt (Columbia River) (eulachon)	*Thaleichthys pacificus*
shad (American)	*Alosa sapidissima*
sturgeon (white)	*Acipencer transmontanus*
yellow perch	*Perca flavescens*
three-spine stickleback	*Gasterosteus aculeatus*
Plankton	
	Daphnia pulex
	Bosmina sp.
Opossum shrimp	*Neomysis awatschensis*

APPENDIX D (CONT.)

Bacteria	
Columnaris	Chondrococcus columnaris
Furunculosis	Dermocystidium salmonis
	Aeromonis salmonicida
Protozoans	
Ceratomyxa	Ceratomyxa shasta
Insects	
Midges	Tendipedidae
Caddis fly	Tricoptera